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Lane, B. H., 1935. Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C., 25c.)

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DECEMBER 1951

LATE GLACIAL ADVANCES IN THE SOUTHERN WIND RIVER MOUNTAINS, WYOMING

JOHN HALL MOSS

ABSTRACT. The record of late glacial events in the southern Wind River Mountains was strongly developed and has been well preserved because of the large area with altitude over 10,000 feet and the relative flatness of glacially cut valley floors in the upper parts of the drainage systems. Studies of glacial deposits many miles upvalley from the large Pinedale moraines reveal evidence of two small but significant ice advances since Pinedale time. The latter of these periods of moraine building is clearly referrable to the "Little Ice Age" which is believed to have reached its climax within the last few centuries. The earlier advance, called the "Temple Lake substage" is considerably older, having an antiquity intermediate between late Pinedale and the present. If Pinedale is equivalent to Mankato (Wisconsin 3), relative weathering characteristics would indicate that the Temple Lake advance occurred just before or soon after the "climatic optimum."

INTRODUCTION

RECENT mapping of Pleistocene deposits in several ranges of the Middle Rocky Mountains has provided a growing body of evidence supporting Blackwelder's original hypothesis of three major glacial advances, which he named Buffalo, Bull Lake, and Pinedale (Blackwelder, 1915). However, this mapping has also revealed that these advances were far more complex than originally supposed and may not in themselves represent the full sequence of Pleistocene glaciation in the area (Richmond, 1948; Holmes, 1949; Moss, 1949b). In particular, it seems increasingly probable that between late Pinedale time and the present, there occurred at least two additional significant swings towards glacial conditions. Studies of the upper reaches of ten valleys in the central and southern Wind River Mountains by J. T. Hack (Hack, 1943) and G. W. Holmes and the author in 1946, 1947, and 1949 have revealed the presence of two small but

distinct sets of moraines that may represent heretofore not fully described late glacial advances in the area. It is the purpose of this paper to describe the evidence for these advances and to present arguments for their significance in the Rocky Mountain glacial sequence.

ACKNOWLEDGMENTS

The investigation reported here is part of a larger investigation of the glacial deposits of the area conducted jointly by the author and G. W. Holmes of Beloit College. The writer is especially indebted to Dr. Holmes and the late Dr. Kirk Bryan for stimulating discussion and valuable criticism in the field. Without the able assistance of J. James, H. B. Stewart, Jr., F. M. Wright, and K. Bryan, Jr., the high altitude mapping could never have been completed. This manuscript has profitted by the constructive suggestions of J. T. Hack, F. Fryxell, L. Horberg, and P. MacClintock. To each of these and to the Viking Fund, which financed much of the work, the writer wishes to express his sincere thanks.

GEOGRAPHIC SETTING

The Wind River Mountains are located in central western Wyoming about 100 miles southeast of Yellowstone Park (fig. 1). They extend southeastward for about 110 miles from Togwotee Pass (latitude 43°45′) to South Pass (latitude 42°30′), forming a barrier between the Bridger Basin on the southwest and the Wind River Basin on the northeast. The range is both high and formidable. It contains at least 13 peaks over 13,000 feet, the foremost of which is Gannet Peak (altitude 13,785 feet), the site of the third largest snowfield in the United States. In the southern third of the range, investigated in this study, there are fewer peaks over 13,000 feet, but relief continues to be great. The roughness of the topography is largely the result of intense glaciation which has so sculptured the range that only three passes traversable on horseback transect its sawtooth backbone along the Continental Divide.

Of particular concern in this report are the glacial deposits in the valley of Big Sandy Creek, a tributary of the

Green River which flows down the southwest slope of the range near its southern extremity. This creek has its origin in a small glacier in a north-facing cirque on Temple Mountain (altitude 12,996 feet). For the first 10 miles of its course, it flows through a series of rock-rimmed lakes lining the floor of a broad U-shaped valley, finally cascading from the mountains in a steep canyon. Flowing across the dissected

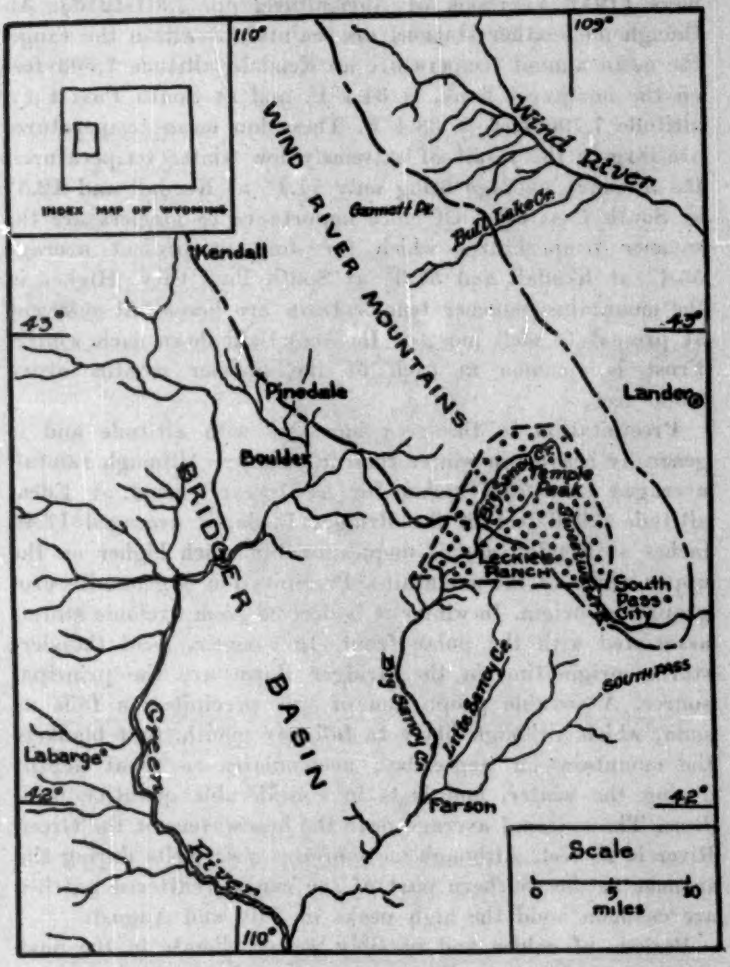


Fig. 1. Index map showing area investigated.

floor of the adjacent Bridger Basin, it follows a meandering southwesterly course to its junction with the Green River about 75 miles from the mountains.

CLIMATE

The present climate of the Wind River Mountains is characterized by long cold winters and short moderate summers (1941 Yearbook of Agriculture, pp. 1201-1210). Although no weather stations are maintained within the range, the mean annual temperature at Kendall, altitude 7,600 feet on the northwest flank, is 34.4°F. and at South Pass City, altitude 7,796 feet, is 33.4°F. These low mean temperatures are largely the result of extremely low winter temperatures, the January average being only 11.4° at Kendall and 12.5° at South Pass City. Of more importance to glaciers are the summer temperatures which for July at present average 55.4° at Kendall and 57.3° at South Pass City. Higher in the mountains, summer temperatures are lower but sufficient at present to melt most of the snow laid down each winter. Frost is common in each of the summer months above 9,000 feet.

Precipitation in the area increases with altitude and is generally heavier in winter than in summer. Although rainfall averaged only 7.05 inches for a 27-year period at Eden, altitude 6,950 feet in the Bridger Basin, it averaged 17.46 inches at Kendall and is unquestionably much higher on the upper slopes of the mountains. Precipitation is generally orographic in origin. In winter it is derived from cyclonic storms associated with the polar front. In summer, local thunderstorms originating in the Bridger Basin are the principal source. A sizeable proportion of this precipitation falls as snow, which although likely to fall any month, first blankets the mountains in September, accumulates to great depths during the winter, and lasts in considerable quantity until June. The seasonal average near the headwaters of the Green River is 23 feet. Although most of the snow melts during the summer in the southern part of the range, scattered patches are common amid the high peaks in July and August.

Periods of colder and possibly wetter climate in the past are recorded by the striking array of glacial landforms which

are conspicuous features of valleys many miles downstream from the small present-day glaciers. It is evident that the Pleistocene in this area, as elsewhere in the Rocky Mountains, has been characterized by an alternation between times of glacial advance with accompanying development of moraines and outwash plains and periods of glacial retreat when trenching of outwash plains formed terraces and morainic deposits were modified by weathering and erosion. It is by no means safe to assume that these climatic changes were

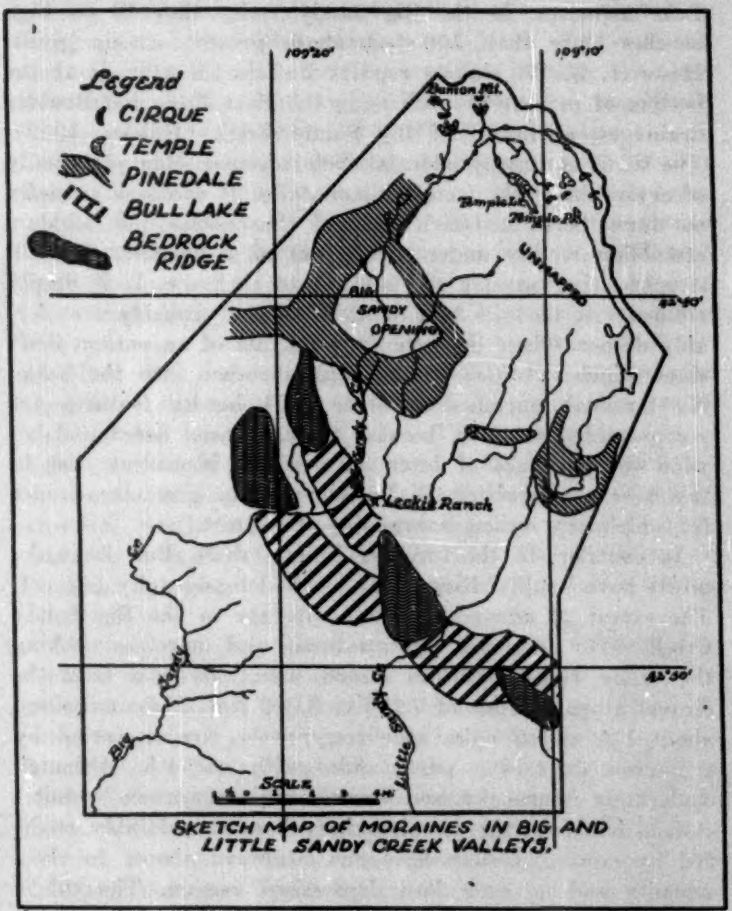


Fig. 2

only characteristic of the distant past, for the accounts of early explorers who visited the area in the middle third of the 19th century described far different summer snow conditions than are found at present. These early accounts are summarized in later paragraphs.

Deposits of the Buffalo, Bull Lake and Pinedale Advances.—Deposits of the Buffalo advance consist of formless patches of compact weathered till lying in the Bridger Basin at an altitude of 7,600 feet about 2 miles downvalley from Bull Lake moraines. In the Big Sandy valley they lie on high benches more than 100 feet above present stream grade. However, G. W. Holmes reports Buffalo till near or at the bottom of present-day valleys in the East Fork and Boulder drainages, northwest of Big Sandy Creek (Holmes, 1950). The till is commonly chocolate-colored, consisting principally of crystalline rocks from the mountains. It contains virtually no unweathered material, most of the cobbles and boulders crumbling readily under the impact of a hammer. The till is extremely compact and difficult to excavate. It is deeply stained with limonite to a depth of 6 feet, probably considerably deeper. These deposits are remnants of an ancient drift sheet which extended an unknown distance into the basin. No terminal moraines or other drift border features are recognizable. However, because these deposits are found beyond the moraines of later advances, it is evident that in this area as elsewhere the Buffalo was the greatest advance for which any record is available at present.

In contrast to the formless Buffalo drift, Bull Lake deposits have readily discernible morainal topography (fig. 2). The extent of advances of this substage in the Big Sandy Creek valley is shown by two broad end moraines choking the valley west of Leckies Ranch, about 25 miles from the cirques at an altitude of 7,700 to 8,000 feet. These moraines, about 1½ and 2 miles wide respectively, are separated by a narrow depression partly filled with outwash. Although moderately hummocky and covered with numerous limonite-stained boulders, the moraines have been considerably modified by erosion. Gullies have cut headward almost to their summits and no undrained depressions remain. The till is compact and moderately weathered. Although stained with

limonite to a depth of about 5 feet, its oxidized zone is usually distinguishable by a lighter color than the Buffalo equivalent. Surface boulders display only thin weathering rinds but about one half of all buried cobbles and boulders in the oxidized zone are easily disintegrated by hand. Associated with each of the Bull Lake moraines is a gravel outwash plain which extends down Big Sandy Creek as an independent terrace.

The youngest of the three principal advances recorded in the Big Sandy Creek valley is the Pinedale, characterized by bold-fronted, little-eroded moraines and loose, slightly weathered till. The Pinedale terminal moraine mantles the slope between Dutch Joe Meadows and the south end of Big Sandy Opening (altitude 8,500-9,150 feet). For convenience, it is here called the Lower Big Sandy Opening moraine. It is a massive bouldery moraine fronted by an outwash plain forming Dutch Joe Meadows. Its position indicates an ice advance of about 10 miles from the cirque headwall above Temple Lake. In contrast to the Bull Lake moraines, the Pinedale has a steep little-dissected front and a hummocky top pitted with numerous kettle holes. Crystalline boulders, which are plentiful, show only a slight degree of weathering, whether they lie on the surface or are buried. Virtually none can be disintegrated by a hammer blow. The moraine consists of light gray sandy till on which 6 to 8 inches of topsoil had developed. Despite greater rainfall at this altitude favoring chemical weathering, limonite staining has extended downward to a depth of only 24-36 inches. The till is loosely packed, relatively easy to excavate and will not hold a vertical face in a cut.

In the Big Sandy Creek valley there was no important halt of the retreating Pinedale ice until it had melted to a point northeast of Big Sandy Opening. Remnants of a few small recessional moraines 10-25 feet high are present in the Opening, but no important halt or readvance of the ice took place until its terminus had retreated to a point 2½ miles upvalley from the terminal moraine. On the riser of a rock step at an altitude of about 9,200 feet a sizeable bouldery moraine (Upper Big Sandy Opening moraine) loops across the valley. It rises about 75 feet above the valley

floor, but some of its height is unquestionably due to its position on the riser. Extending outward from this moraine is a broad outwash plain which can be traced continuously three miles downstream. As the topographic expression of this moraine and degree of weathering of materials comprising it closely resembles the Lower Big Sandy Opening moraine, they are both assigned to the Pinedale substage.

Above the Upper Big Sandy Opening moraine, no further halts or readvances are recorded for about 8 miles upvalley, or to a point within 2 miles of the cirque headwalls. As these last moraines are significantly different in character from the Big Sandy Opening moraines, it is believed they represent considerably later episodes of moraine building. Apparently after forming the upper Big Sandy Opening moraine, the ice front retreated steadily for some time without notable halt.

Temple Lake Moraines.—As pointed out above, although

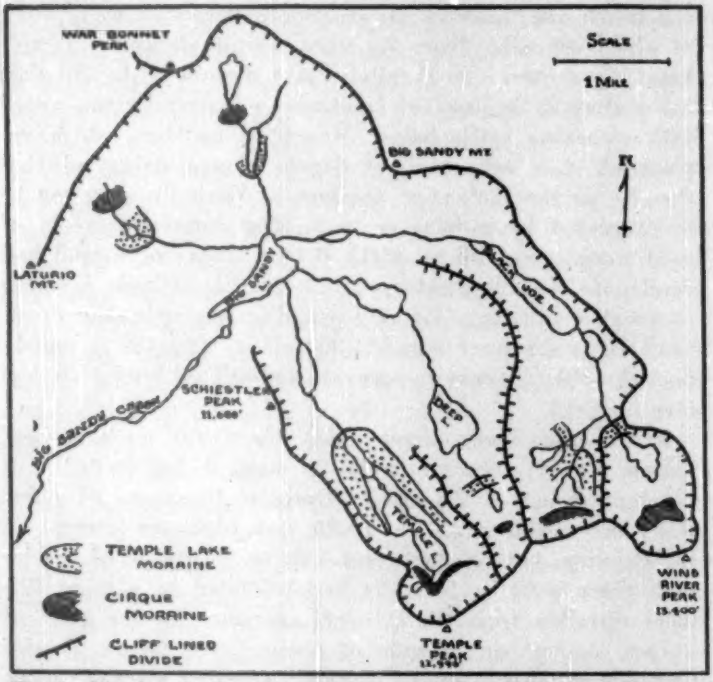


Fig. 3. Moraines in the upper reaches of the Big Sandy Creek drainage system.

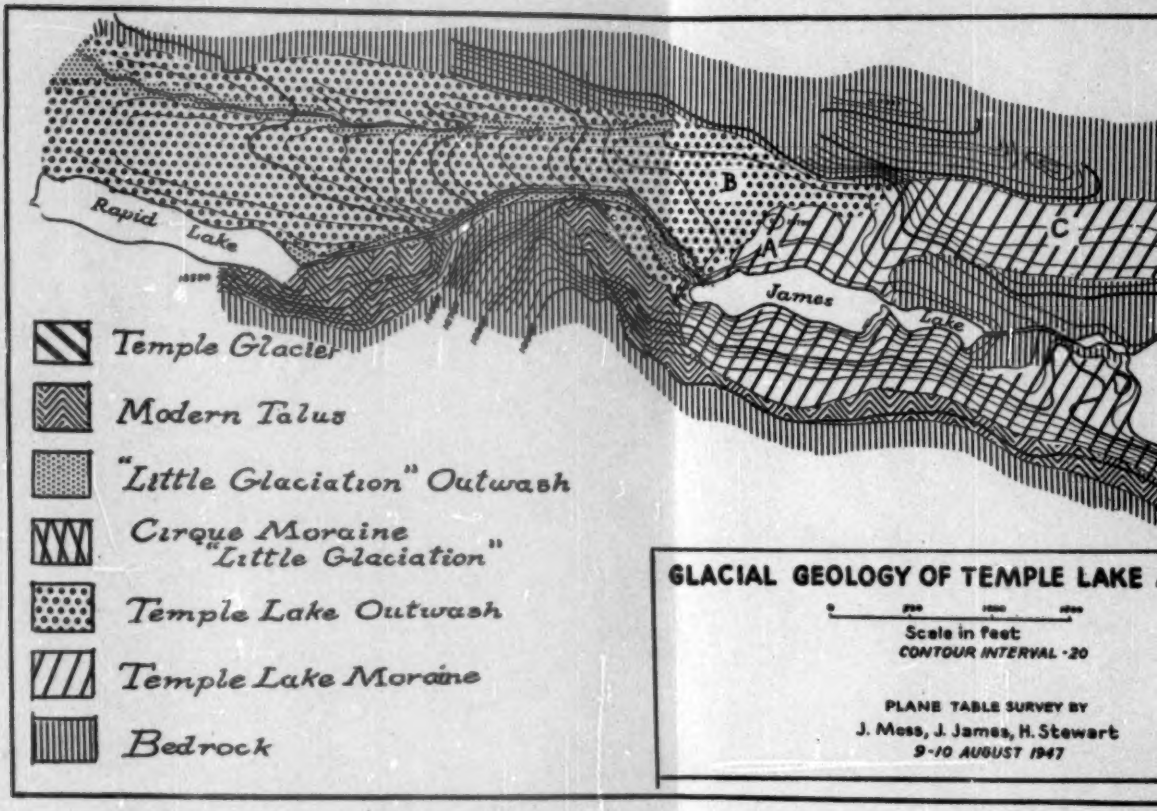
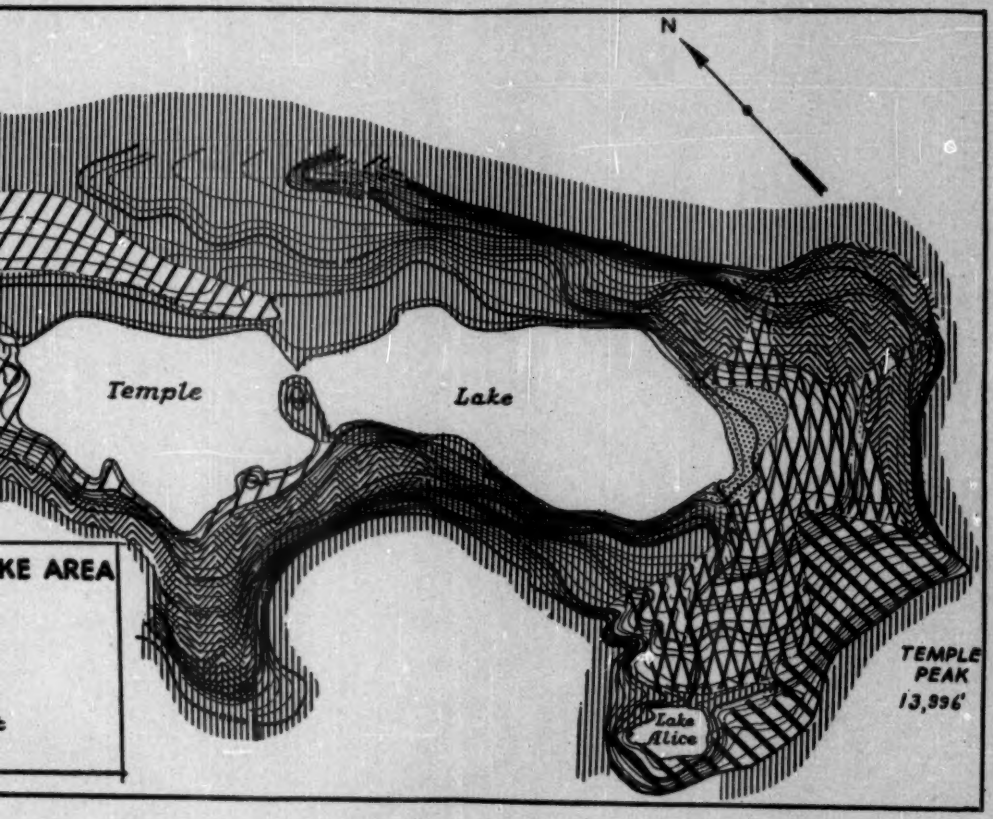

Rapid Lake
B
A
C
James Lake
Temple Glacier
Modern Talus
"Little Glaciation" Outwash
Cirque Moraine "Little Glaciation"
Temple Lake Outwash
Temple Lake Moraine
Bedrock
GLACIAL GEOLOGY OF TEMPLE LAKE
Scale in feet
CONTOUR INTERVAL - 20
PLANE TABLE SURVEY BY
J. Moss, J. James, H. Stewart
9-10 AUGUST 1947

Fig. 4


N
Temple
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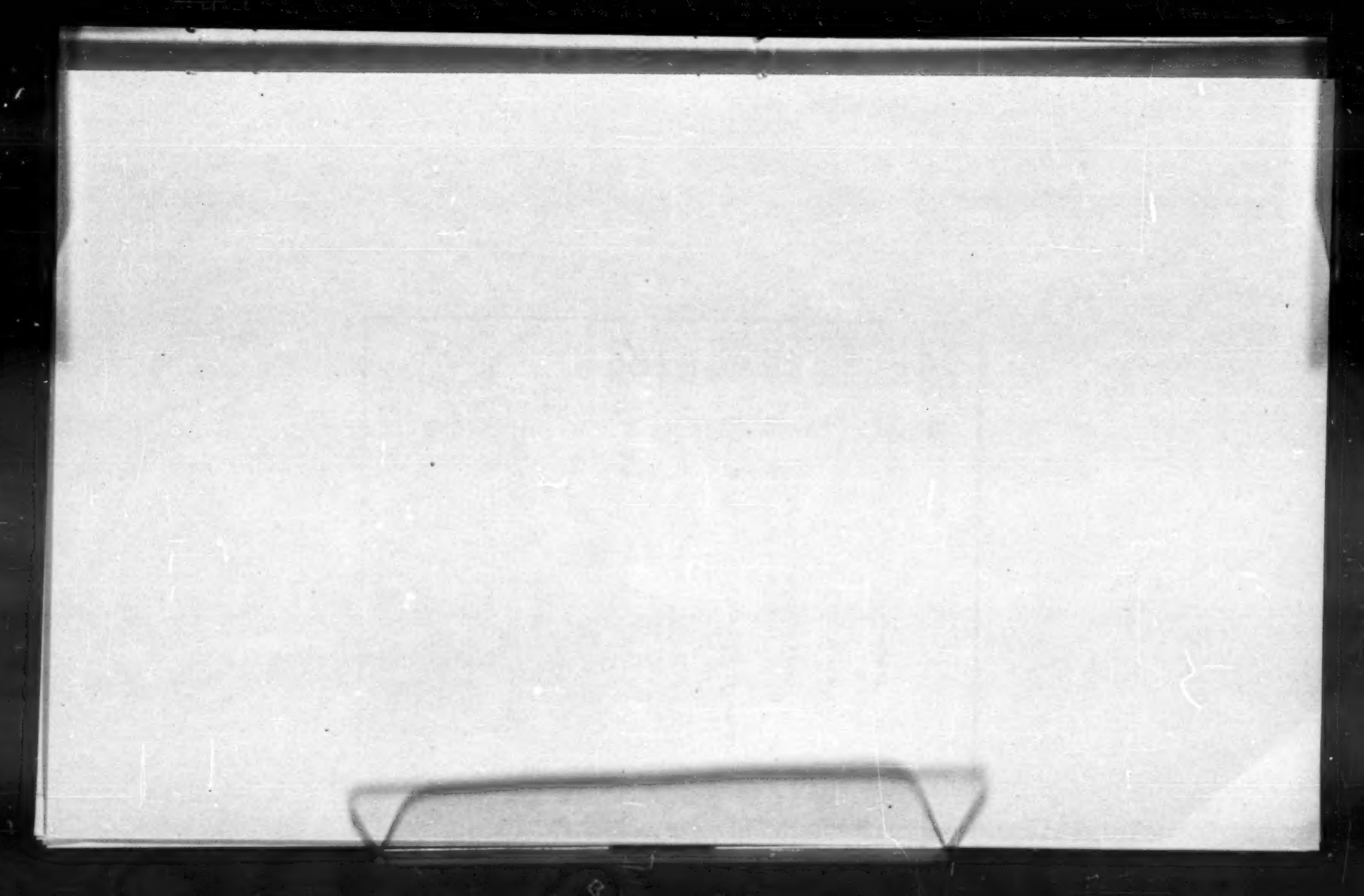

Buffalo, Bull Lake, and Pinedale deposits have been distinguished in many valleys in the Middle Rocky Mountains, post-Pinedale events in the area are still not clearly understood. This circumstance is due to the general inaccessibility of the upper parts of many valleys, and the non-deposition or subsequent erosion of later deposits. The southern Wind River Mountains has proved to be an advantageous place to study these events because: (a) the range is high enough to have been subjected to later minor glaciation and (b) several of the upper valleys have broad flat floors at high elevations ideally suited for the preservation of post-Pinedale deposits. In discussing these late glacial deposits in the area, the sequence in the upper Big Sandy Creek valley will first be described after which similar deposits in other valleys will be discussed to show their widespread occurrence in this part of the range.

As pointed out above, a large gap separates the massive Pinedale moraines in the Big Sandy Creek valley from the small but distinct later deposits in the upper valleys. Near Temple Lake (altitude 10,770 feet) about 1½ miles downvalley from the remarkably fresh moraine fronting Temple glacier, a more prominent crescent-shaped moraine blocks the valley leading from the north-facing cirque of Temple Mountain (figs. 3 and 4). As this moraine and its associated outwash plain dams Lower Temple Lake (James Lake) on the north, it was tentatively named by Hack the Temple Lake moraine and the ice advance marked by it the Temple Lake Substage (Hack 1943, p. 239). Figure 4 is a plane table and alidade map of the moraine and enclosing valley. The frontal portion of the moraine "A", rising about 50 feet from the outwash plain "B", consists principally of a loop of gigantic angular blocks, commonly 20-40 feet in greatest diameter and displaying a variety of crystalline rock types. The surfaces of the boulders are slightly stained with limonite and generally covered in part with lichens. As small patches of till lie among the blocks, particularly near their bases, it seems probable that the stream which flows through the frontal portion of the moraine has removed most of the finer components of the till. Further evidence for this is the gently sloping grass-covered outwash plain "B" which ex-

tends from the moraine to the precipitous drop to Big Sandy Lake. This outwash plain consists largely of sand gravel and cobbles, but a few boulders protrude through the surface of the turf. Extending up both sides of the valley from the loop of blocks are lateral moraines. On the west the lateral moraine is capped with blocks while on the east, "C", it consists of finer grass-covered till.

The deposits laid down during this advance are generally very bouldery, due apparently to the short distance the material was transported and the action of meltwater in removing much of the fine material at many localities. Even in the lateral moraine, "C", where the till appears to be relatively unwashed, it contains less than 4 per cent silt and clay size particles. The till is light gray in color and where not too bouldery, supports a thin topsoil up to 4 inches thick. Below the topsoil, the till is stained with limonite to a depth of 10-12 inches. This contrasts with a general average of 6 inches of topsoil and 24-36 inches of limonite staining in Pinedale till.

If such a moraine were limited to the Temple Lake valley, it might be discounted as resulting from local factors peculiar to this part of the valley. Similar steep-fronted moraines, however, are conspicuous in the adjacent Deep Lake and Black Joe valleys, which also extend northward from north-facing cirques (fig. 3 and plate 1). These moraine lie at approximately the same altitude and distance from the cirques as in the Temple Lake valley. In addition, prominent curving moraines of this substage, 50-90 feet high, lie in front of south-facing cirques south of Arrowhead and Blue Lakes. Furthermore, recent investigations of the upper reaches of the Sweetwater drainage system by G. W. Holmes and the author revealed the presence in this area too of comparable bouldery moraines well upvalley from those of the Pinedale substage but downvalley from the small fresh moraines fronting existing ice. These steep-fronted, little-weathered moraines line in front of cirques on Larsen and Blair Creeks and on the Sweetwater and East Sweetwater Rivers at altitudes of about 10,000 feet. In the central Wind River Mountains, Holmes reports a moraine of similar position and appearance in the valley east of Mt. Geike (Holmes, 1950). Further

north in the range Richmond reports apparently comparable moraines but does not specify in what valleys they occur (Richmond, 1948). In the Tetons, owing to the steep declivity of the upper valleys, conditions are generally not favorable for the development and preservation of late glacial moraines. However, Fryxell reports end moraines near the termini of several existing glaciers (Fryxell, 1935). In the case of the Teton glacier, he notes that it has a double moraine, the outer of which, a few hundred yards outside the present one, is somewhat more stable and weathered than the adjacent end moraine (Fryxell, personal communication). However, he believes that the difference in age between the two is not great and the outer one may well not correspond to the Temple moraines in the Wind Rivers.

In addition to constructional features, the Temple Lake substage is further represented by nivation hollows and small secondary cirques cut into the walls of the compound Pinedale cirques. These rudimentary basins, lying between 11,000 and 12,000 feet, are particularly well displayed on the walls of the huge compound cirque in which Big Sandy Lake lies. They are easily recognized by their fretted appearance in contrast to the smooth, in places polished, walls not affected by this later ice action. No moraines front these hollows, either because the ice in them was not active enough to build up moraines or because the cirque-forming processes did not progress far enough to produce a sufficiently flat floor on which to build up morainal deposits.

Other erosional features produced by the Temple Lake ice advance are polished surfaces less weathered than those produced by Pinedale ice and lines of boulders along moderately sloping valley walls marking the height to which Temple Lake ice filled the valleys. These features indicate that the advancing Temple Lake ice, although considerably smaller than the Pinedale, was nonetheless active and capable of both eroding and polishing the valley walls.

Cirque Moraines.—The youngest moraines in the Big Sandy drainage area are located at the heads of all valleys, commonly 50 to 300 feet in front of the dwindling ice masses and 750 to 1,000 feet from the cirque headwalls (figs. 2 and 3 and plate 2). They are usually multiple. Their altitude ranges

from 10,750 to 11,000 feet. Because of their location, they are here called the Cirque moraines. They are distinguished from Temple Lake moraines by being smaller, virtually unweathered and less compact.

The lower part of the moraines, which are generally about 30 feet high, consists of gray sandy till showing no visible signs of weathering and an extremely small percentage of fines (2%-3%). Overlying the till is a cap of boulders, or protalus rampart, which when the ice was at its maximum probably fell from the cirque walls and rolled to the moraine. In contrast to boulders on the Temple Lake moraines, which are generally firmly lodged, many of the boulders of the Cirque moraines are so precariously balanced as to make climbing hazardous. The boulders are neither covered with lichens nor stained with limonite. No soil has been developed on the tills although Temple Lake till at the same altitude supports grass and in some places trees. All evidence indicates that the Cirque moraines are extremely young, the ice having retreated from them within the last 100 years.

Table 1 summarizes the outstanding characteristics of the five tills and four sets of moraines in the Big Sandy valley.

Antiquity of the Pinedale, Temple Lake, and Cirque Moraines.—In the absence of Carbon-14 studies on datable materials from either the Pinedale, Temple Lake, or Cirque moraines, the antiquity of these deposits is somewhat conjectural. However, on the basis of degree of preservation of morainic topography and depth of weathering of till, most investigators have tentatively assigned the Pinedale to the late Wisconsin or Mankato (Flint, 1947). The Cirque moraines resemble small very fresh moraines fronting existing glaciers in the Sierra Nevada which Matthes believed were formed following a rebirth of the ice in the interval since the climatic optimum (Matthes, 1939). He named this minor glacial episode "The Little Ice Age" and from a study of geologic evidence and historical records reached the conclusion that it reached its maximum in the 17th, 18th, and 19th centuries.

That the climate in the Wind River Mountains was colder —especially in summer—in the 19th century than at present is recorded in the diaries of early explorers and first survey

TABLE 1

Weathering of Boulders	*Dissection by Big Sandy*	*Moraine Topography*	*Substage*	*Altitude of Moraine*	*Depth of soil*	*Depth of Oxidation*
None	Negligible	Completely unmodified	"Little Glaciation" (Cirque moraine)	11,000	None No lichens on boulders	None
Slight surface staining	Shallow valley in end of moraine	Strong, little modification	Temple Lake	10,500-10,800	4 inches Lichens on boulders	10-12 inches
Slight surface staining	Valley 27′ deep	Strong only slight modification	Upper Big Sandy Opening (Pinedale II)	9,200	6-8 inches	24-36 inches
Slight surface staining	Valley 100′ deep	Strong only slight modification Abundant kettles	Lower Big Sandy Opening (Pinedale I)	8,500-9,150	6-8 inches	24-36 inches
Many, but not all, can be disintegrated by hammer blow	Valley 400′ deep	Moderately strong to subdued No kettles	Upper Leckie Ranch (Bull Lake II)	8,000	8-12 inches	at least 60 inches
Many, but not all, can be disintegrated by hammer blow	Valley 300′ deep	Subdued No kettles	Lower Leckie Ranch (Bull Lake I)	7,700	8-12 inches	at least 60 inches
			Buffalo	no moraines	6-10 inches	at least 55 inches
Virtually all buried boulders can be disintegrated by hand	Deposits 300-600 feet above Big Sandy	No topographic expression				probably much more

parties in the Bridger Basin. These accounts reveal that considerably more snow remained in the mountains in summer during the 19th century than at present. Captain Bonneville, the first man to cross South Pass with wagons, commented on the snow capping the hills flanking the Sweetwater River on July 12, 1832 and wrote as follows of his first view of the mountains on July 20 of the same year: "To the west rose the Wind River Mountains, their bleached and snowy summits towering into the sky." (Irving, 1861, p. 58). Rev. Samuel Parker, approaching South Pass from the east on the Oregon Trail on August 4, 1835 described the appearance of the mountains thus: "Their tops are covered with perpetual snow, which are seen on our left and before us." (Parker, 1838, p. 72). Captain John C. Fremont in the narrative of his exploring expedition of 1842 describes the following view on leaving his camp near South Pass on August 7, 1842: "As we rose from the bed of the creek, the snowline of the mountains stretched grandly before us the white peaks glittering in the sun." (Fremont, 1845, p. 39). At present no snow is visible in July and August from the vicinity of South Pass. The high peaks of the Gannet group which do retain a partial cover of snow throughout the year are over 50 miles distant and hidden by intervening peaks.

Further evidence for the abundance of summer snow in the mountains later in the 19th century is contained in the records of the Hayden Survey. Endlich, who explored the southern part of the range, noted on July 27, 1877 that the lakes above 10,500 feet around the highest peak in the area (Wind River or Temple Peaks) were frozen and that snow covered the upper 1,000 feet of the peak to an estimated depth of 100 feet (Endlich, 1879). Local inhabitants have no recollection of seeing snow on these peaks in late July and August during the last 25 or 30 years and the temperature of the water at a depth of 6 inches in Temple Lake, altitude 10,700 feet, on August 10, 1947 was 53°F.

On the basis of both the geological and historical evidence cited, the formation of the Cirque moraines is here assigned to the recent maximum of the "Little Ice Age", from which the ice is now retreating.

This minor glaciation was not confined to North America,

as between 1600 and 1850 the glaciers in the western Alps overran settlements occupied since the beginning of history and in the eastern Alps and Iceland reached the moraines of the Late Glacial stages (Brooks, 1949, p. 301). Since the middle of the last century glaciers have generally been in retreat in all parts of the world.

The age of the Temple Lake moraines is more controversial. Three possibilities are worthy of consideration: (1) they were formed during the recent maximum of the "Little Ice Age", (2) they were formed during a hitherto unrecognized early maximum of the "Little Ice Age", (3) they were formed in the interval between the Pinedale maximum and the climatic optimum[1].

The most significant evidence for the age of the Temple Lake moraines is the 2 to 3 inches of soil and 10 to 12 inches of limonite staining in the till. This contrasts with no soil and no limonite staining in the Cirque moraines. The greater weathering characteristics of the Temple Lake deposits would certainly require an antiquity of more than a few hundred years and rules out the possibility that the Temple Lake and Cirque moraines were both formed during the recent maximum of the "Little Ice Age."

A more plausible hypothesis is that the Temple Lake advance represents a much earlier pulsation of the "Little Ice Age." If this is true, it follows that the greatest advance of the Little Ice Age" was not the one from which the ice is now withdrawing, but a much earlier one, probably soon after the optimum. However, according to Matthes: "The climax of this period of reglaciation fell in the 17th, 18th and 19th centuries as has been definitely determined in Europe. The glaciers then attained their greatest extension since Pleistocene times and physiographic evidence indicates that this was probably also true in North America, South America, and New Zealand." (Matthes, 1945, p. 1181).

Recent climatic studies in Europe, however, have shown

[1]The climatic optimum, or time of greatest warmth since the Wisconsin maximum is believed to fall in the interval 2,500 to 6,000 years ago. (Antevs, 1948). During this interval numerous lakes in the western part of the United States dried up and all but the largest glaciers in the Rocky Mountains probably disappeared (Matthes, 1941). "The Little Ice Age" had its origin after the climatic optimum.

that in addition to the period of severe climate referred to by Matthes, a second period of climatic stress occurred earlier in the post optimum interval. About 500 B. C. a great deterioration of the climate of northern Europe took place. Willett notes that the onslaught of the glacial weather pattern was so sudden that the rapid advance of the Alpine glaciers was quite catastrophic in its local affect. Elsewhere in the world, numerous new glaciers were formed (Willett, 1946, p. 102). Brooks points out that at this time Lake Constance rose 30 feet, most of the lake villages were destroyed, and settlement in the Alps reached a minimum. Lake Constance did not return to its present level until the first century A.D. (Brooks, 1949, p. 300). In the southwestern part of this country, although evidence on temperature changes is absent, the rapid growth of trees between 480 and 250 B.C. indicates that precipitation reached its absolute maximum since 1000 B.C. Brooks attributes this period of stress to the sudden reappearance of permanent ice in the Arctic Ocean and suggests that although short, this was probably the most severe climatic episode in the postoptimum interval. Antevs reports, however, that in Sweden, according to Granlund, although precipitation had its postglacial maximum in the centuries just before Christ, the Scandinavian glaciers did not attain their greatest postglacial size until the period 1745 to 1825 (Antevs, 1948). Clearly more climatological data are needed to evaluate the probable effect of this earlier stormy period on the Rocky Mountain glaciers.

The hypothesis that Temple Lake moraines represent a late readvance of the ice before the climatic optimum is perhaps to be preferred. It is noteworthy that the weathering characteristics of the Temple Lake deposits resemble more closely the Pinedale than the Cirque moraines. However, as thickness of topsoil and depth of staining of Temple Lake till is generally about one-half that of Pinedale, this advance must have taken place late in the interval between the Pinedale maximum and the climatic optimum. Richmond has assigned presumably comparable moraines in the northern Wind Rivers to what he calls the Pinedale 3 stage, Pinedale 1 and 2 apparently correlating with the Lower and Upper Big Sandy Opening moraines in the Big Sandy drainage

PLATE 1. Temple Lake moraine in Black Joe Valley. Moraine is about 75 feet high. Smaller Cirque moraine of "Little Glaciation" lies ½ mile upvalley near base of cliff in right background.

PLATE 2.

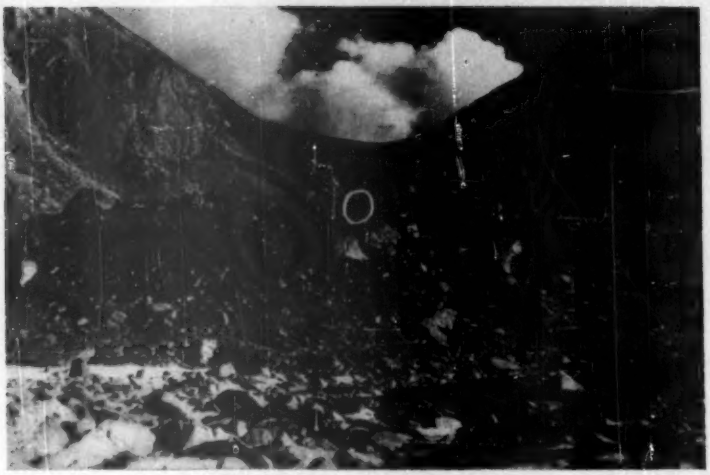

Fig. 1. Front of Temple Lake moraine in Black Joe Lake valley. Size of moraine is shown by contrast with man in circle.

Fig. 2. View of Cirque moraine fronting existing ice at head of Black Joe Lake valley. Man in middle-ground is standing on ground moraine of Temple Lake substage. Note contrast between grass-covered Temple Lake deposits and unweathered precariously balanced materials in Cirque moraine.

(Richmond, 1948). In the middle and southern part of the range, however, this threefold subdivision is not everywhere as valid as many valleys have more than three prominent Pinedale moraines and Temple Lake deposits are notably less weathered than Pinedale 1 and 2 which closely resemble each other.

Hack, on the basis of what he called the "briefest sort of reconnaissance" (1943, p. 240) tentatively correlated the Temple Lake advance with Ray's Long Draw substage in the Southern Rockies (Ray, 1940). This latter substage is represented by moraines which generally correspond in altitude, valley position, and weathering characteristics with Temple Lake moraines. Although the evidence is admittedly tenuous, Bryan and Ray tentatively correlated the Long Draw substage with the Cochrane readvance in Canada and the Fennoscandian end moraine in Sweden (Bryan and Ray, 1940). On the basis of this correlation, Temple Lake would be post Mankato (Wisconsin III) in age, representing a small very late glacial advance.

In conclusion, until the importance of the stormy period in the first century B.C. can be more fully evaluated, the Temple Lake moraines are best assigned to a minor glacial episode late in the interval between the Pinedale maximum and the climatic optimum (table 2). Now that similar moraines of this age have been discovered in New Mexico, Colorado, and Wyoming, it is hoped that future glacial studies in the Middle and Northern Rockies will include investigation of the upper valleys near the cirques to determine whether correlatives of the Temple Lake substage are present.

TABLE 2

Summary of late glacial substages in southern Wind River Mountains

Big Sandy Creek	*Wisconsin Substage*
Cirque - "Little Ice Age"	W 5
CLIMATIC OPTIMUM	
Temple Lake	W 4
Pinedale	W 3

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Franklin and Marshall College
Lancaster, Pennsylvania

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FAULTING IN THE LOST RIVER RANGE AREA OF IDAHO

EWART M. BALDWIN

ABSTRACT. Faulting similar to that of the Basin and Range geologic province is present in the Lost River Range area in central Idaho north of the Snake River Plain. At least two stages of faulting are present. The older stage preceded the extrusion of the Challis volcanic series of late Oligocene or early Miocene age and is expressed by normal faults, tear faults and minor thrust faults. Large normal faults transverse to the trend of the ranges have not appreciably displaced either the Challis volcanics or the prominent post-volcanic erosion surface. The tear faults and thrust faults evidently formed during the deformation of the Paleozoic strata at the end of the Mesozoic and the pre-Challis normal faults may have formed in a late stage of Laramide orogeny. The younger faults have displaced both the Challis volcanics and the erosion surface, forming the present broad basins and fault-block ranges.

The large scale faulting indicated by this study leads to a conclusion different from that of recently published accounts suggesting an erosional origin for the present basins and ranges without aid of large scale faulting.

INTRODUCTION

THE purpose of this paper is to show in some detail the fault pattern in the Lost River Range and adjacent parts of central Idaho. The fault pattern as well as certain aspects of the stratigraphy as interpreted by the writer differ markedly from that published by Ross (1937, 1947). The faulting is similar to that in the Basin and Range geologic province in southern Idaho and Nevada.

TOPOGRAPHIC SETTING

Several northwest-trending mountain ranges and broad intermontane valleys are located north of the Snake River Plain and east of the Idaho batholith. Of these ranges, the Lost River Range is one of the most prominent. It extends from the Salmon River near Challis, Idaho, to the Snake River Plain near Arco, a distance of some 80 miles. Borah Peak in this range, elevation 12,655, is the highest peak in Idaho. The Lemhi Range to the northeast parallels the Lost River Range and beyond this lies the Beaverhead Mountains whose crest is the state line between Idaho and Montana. The

White Knob Mountains and Lone Pine Peak lie to the south and southwest. Drainage in the area discussed is about equally divided between the Salmon River to the northwest by way of Warm Springs Creek and the Pahsimeroi River and the Snake River Plain by way of the Big and the Little Lost Rivers. Both rivers sink into the alluvium on reaching the plain.

Each individual range has an abrupt scarp-like front overlooking a broad intermontane basin along its southwest border and with a more irregular dissected erosion surface sloping to the northeast. The intermontane trenches have straight borders next to the southwest sides of the Lost River and Lemhi ranges, but the edges of the trenches are more irregular where the back slopes of the tilted mountain blocks meet the alluvial plain. Lone Pine Peak is an exception, for a prominent fault is on the northeast side and its scarp faces the scarp of the Lost River Range, which is located about 6 miles across Warm Springs valley. The Pahsimeroi and Little Lost River valleys average 5-8 miles in width. The Big Lost River valley is in places much narrower than the others, particularly between the Mackay Reservoir and Mackay, but in the Thousands Springs Valley and southeast of Mackay the valley widens and is about the same width as the other wide valleys in this part of Idaho.

Drainage divides between the streams flowing within the intermontane basins are insignificant when compared with passes through the ranges. The Pahsimeroi and Little Lost River valleys are connected on either side of the Donkey Hills by a low pass which rises but a few hundred feet above the valley floors. Willow Creek Summit between the Thousand Springs Valley and Antelope Flat drainage presents a more abrupt rise, but it too is comparatively low.

During the geologic reconnaissances in this area which preceded more detailed work, various interpretations of the structure and geomorphology were presented. Umpleby (1917, p. 19) considered the broad valleys to be carved in an earlier formed peneplain. Kirkham (1927) suggested that the Lost River Range was bordered by steep reverse faults consistent with the wedge-theory of diastrophism. Anderson (1934) recognized faulting of the Basin Range type and indicated

that a prominent fault bordered the southwest side of the Lemhi and Lost River Ranges and indicated that a similar fault pattern extended even into the batholith area to the west. However, the most exhaustive study of the Lost River Range and adjacent area by Ross (1937, 1947), who mapped the Bayhorse and Borah Peak quadrangles, failed to convince him that a prominent fault paralleled the Lost River Range or adjoining basins to the southwest. Further evidence is here

TABLE 1

Stratigraphy of the Borah Peak Quadrangle

	Ross (1947, p. 1095) Thickness in feet	Baldwin Thickness in feet
Quaternary		
Recent alluvium	0–100+	0–750
Glacial deposits	.....	0–1000
Unconformity		
Tertiary		
Donkey fanglomerate (Pliocene ?)	0–1000+	.....
Unconformity		
Challis volcanics (late Oligocene or early Miocene)		0–2000
Germer tuffaceous member	0–500+	
Basalt and related flows	2500±	
Latite-andesite member	1000±	
Unconformity		
Pennsylvanian		
Wood River formation	500+	.....
Mississippian		
Brazer limestone	4000±	3500+
Milligen formation	1000±	2400±
Devonian (Upper Devonian)		
Three Forks limestone	20–350	310[2]
Grand View dolomite	2000+	1100[3]
Jefferson dolomite	1000+	1350[3]
Silurian		
Laketown dolomite	600[1]±	2450[3]
Ordovician		
Saturday Mountain formation (Upper Ordovician)	500–700	0–300
Kinnikinic quartzite (Upper Ordovician)	3000±	4635+
Ramshorn (?) slate (Lower Ordovician)	2100+	0–2300[4]
Unconformity		
Precambrian quartzite series		

[1]Given in table by Ross as 6,000 feet, but on page 1106 the figure is 600+ feet.

[2]Measured 1 mile east of Freighter Spring (Baldwin, 1943).

[3]Measured east slope of Mahogany Hill.

[4]Includes quartzite and slate. This series is tentatively assigned by the writer to the Cambrian for it unconformably lies beneath Kinnikinic quartzite (plate 1, fig. 1).

presented to show that faulting of the Basin Range type is present and that it causes the linear mountain ranges and intervening trenches.

RESUME OF STRATIGRAPHY

Extensive sections of Precambrian quartzites are exposed in the Lemhi Range. The rocks in the Donkey Hills and Lost River Range are predominantly Paleozoic. Quartzites, dolomites, and sandy shales, sandstone, and limestone are the principal types of rock present (table 1). Tertiary lava flows and pyroclastics with associated basin sediments occupy the troughs in the older rock and they are in many places covered by more recent alluvium contributed by streams from the ranges largely as alluvial fans.

The formations are well displayed in the scarp of the Lost River Range for, with few exceptions, the border fault parallels the axes of the folds. The Ordovician quartzite is beneath the surface along most of the range, but the overlying Silurian and Devonian dolomites form the "buttresses" noted by Ross (1947, plate 2). The Three Forks, Milligen, and Brazer formations are relatively incompetent formations and are much more closely folded, particularly in the centers of the synclines. Most of the crest of the Lost River Range is capped by the Brazer limestone. The normal sequence of formations is shown in plate 1, figure 2.

An exception to the usual sequence is present between Leatherman Pass and Rock Creek in the area including and surrounding Borah Peak. Here the formations are badly broken by faults and thick sections of Kinnikinic quartzite and older formations are exposed. Ross (1947, p. 1099) discussed this section and referred to the quartzite units as the "light colored quartzite with pebbles", "the purple quartzite", and the "white quartzite". The stratigraphy of this part of the range (Ross, 1947, fig. 2) does not seem to be as obscure as shown by Ross, particularly if the relationship to the frontal fault is taken into consideration. The oldest of the three quartzite units exposed is made up of hematite flecked, pebble bearing, light pink to white quartzite which in the main underlies but is intercalated with dark greenish-gray slate. This series crops out near the head of Vance Canyon

where a few hundred feet of slate lie within a synclinal fold in the quartzite and both are unconformably covered by purple Kinnikinic quartzite (plate 1, fig. 1). This quartzite and slate series is also exposed along the mountain just west of the mouth of Sawmill Gulch at a much lower elevation. That the quartzite is associated with the slate cannot very well be doubted, for similar quartzite lenses are found interbedded with the slate. The thickness is difficult to tell because of probable duplication, but the quartzite and slate together are probably 2,000 or more feet thick as estimated by Ross.

The thick Kinnikinic quartzite (which is a thoroughly indurated sandstone) caps the mountain top between Leatherman Pass and Pass Lake. It is well exposed in the cirque at the head of Vance Canyon. Here purple quartzite of varying hues is overlain by vitreous white quartzite. Within the mass are lenses of rusty dolomite, one lens being nearly 400 feet thick. Talus of the Kinnikinic quartzite obscures the relationship between it and the underlying slate but there can be little doubt it is unconformable.

Blocks of the "purple" and the "white" quartzite are duplicated several times along the face of the mountain (plate 1, fig. 1). Rusty impure quartzite occurs along the east side of Sawmill Canyon which resembles the Precambrian quartzite of the Lemhi Range, and it may be of this age for it does not fit into any of the series described.

The quartzite associated with the slate has been compared by Ross with the Swauger quartzite of the Lemhi Range of supposed Precambrian age. However, the slate is strikingly similar to the Ramshorn slate of the nearby Bayhorse quadrangle to which Ross assigned a Lower Ordovician age on the basis of a sparse fauna found in the southern part of the quadrangle where the slate is carbonaceous in places and parts parallel to bedding. The association of the slate and quartzite, similar to the Ramshorn slate and associated quartzite in the Bayhorse quadrangle makes it difficult to accept both correlations, for no break has been proposed between the two rock types, either here or in the Bayhorse quadrangle. It might be that the Swauger quartzite is not as old as supposed. Ross (1937, p. 15) considers the possibility that the lower part of the Ramshorn slate and associated

PLATE 1

Fig. 1. Lost River Range showing segment near Pass Lake which lies behind the peaks. Purple (p) and white (w) Kinnikinic quartzite with intercalated dolomite within the white member at the top of the peaks. The Leatherman Pass fault separates the Ordovician strata on the left from the Mississippian strata (Cb). Slate in upper Vance Canyon overlying associated quartzite lies unconformably beneath the Kinnikinic quartzite. In the foreground a small faultblock of Kinnikinic quartzite rests against the darker quartzite that is associated with and underlies the slate.

Photo by A. L. Anderson

Fig. 2. Lost River Range at the mouth of Upper Cedar Creek with Mt. McCaleb in center. The Lost River Fault lies beneath the alluvium at the front of the range. *C*, Mississippian; *D*, Devonian; *S*, Silurian.

Photo by A. L. Anderson

PLATE 2

Fig. 1. Fault scarp along northeast side of Lone Pine Peak from Antelope Flat.

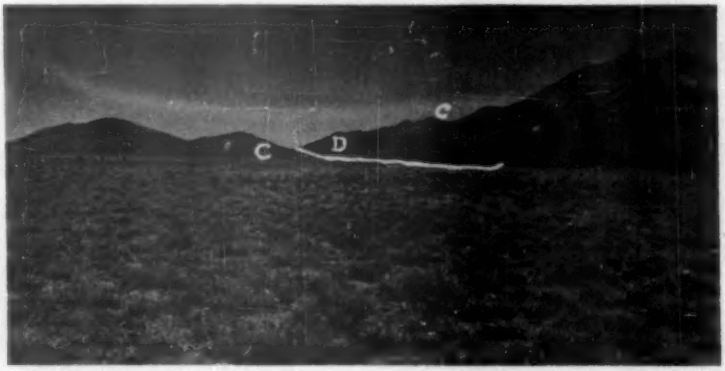

Fig. 2. Willow Creek Summit from Thousand Springs Valley. The fault along the southwest side of the Lost River Range passes behind a low ridge in the central right side of the photo. Dickey Peak to the right. *C*, Mississippian; *D*, Devonian.

Photo by A. L. Anderson

quartzite might be of Cambrian age. The writer favors the Cambrian age because of the unconformable relationship of the overlying Kinnikinic and the greater degree of metamorphism in the underlying beds.

RESUME OF FOLDING

Precambrian formations are unconformable beneath the Paleozoic section, yet are not deformed much more than the less competent formations of the Paleozoic. There is a suggestion that some folding did take place after the deposition of the Ramshorn slate because of the extent of metamorphism exhibited by the well-developed slaty cleavage and because of the unconformable relationship of overlying strata in Vance Canyon.

Most of the deformation occurred during the Mesozoic, much of it prior to the intrusion of the Idaho batholith, according to Ross (1947, p. 1125), who favored deformation prior to the Laramide folding to the east. The age of the batholith is given as Late Jurassic or Early Cretaceous by Ross (1928, p. 674). Formations in southeastern Idaho which appear to be along the same general structural trend were deformed during the Laramide according to Mansfield (1927). It would appear logical to suppose that the Lost River Range, because of its proximity to Laramide folding, would also have been further deformed during this orogeny. Anderson (1948, p. 84) discussed the role of the batholith during Laramide orogeny and concluded that compression during this time resulted in further folding, thrusting, and development of shear zones particularly in and along the margins of the batholith where it acted as a buttress. If Jurassic deformation in the west advanced progressively eastward culminating in Late Cretaceous diastrophism in the Rocky Mountain region as suggested by Longwell (1950, p. 424), the Lost River area would occupy an intermediate position.

Miocene to early Pliocene deformation is indicated by warping of the Challis volcanic series of late Oligocene or early Miocene age. Brown (quoted in Ross, 1937, p. 66) correlated the flora of the Challis series with several formations considered to be lower Miocene. He states that "the general aspect of this collection indicates a probable upper

Oligocene or lower Miocene age." He considers its younger age limit pre-upper Miocene. The Challis strata commonly dip 10-25 degrees although some dips are steeper near zones of faulting. Mansfield (1927, p. 19) records a stage of warping during the middle Miocene of southeastern Idaho.

RESUME OF FAULTING

There are at least two sets of faults in the Lost River Range area. One appears to have been formed during Laramide and earlier deformation and is expressed by tear faults, normal faults, and thrust faults. The displacements occurred prior to the extrusion of the Challis volcanic series, do not offset the post-Challis erosion surface and in some cases do not offset the pre-Challis erosion surface. These are referred to as pre-Challis. Faults of the second set are of the Basin Range type. They are expressed by prominent scarps, the largest of which border tilted faultblock mountains and some of the basins as Thousands Springs Valley. The initial stage of faulting must have occurred during or soon after extrusion, as the Challis volcanic series is present in the downfaulted areas and missing elsewhere. These faults are referred to as the post-Challis faults.

Large scale overthrusting which is found in the nearby Rocky Mountains was not recognized in the Lost River Range. Several minor low-angle thrust faults were noted. Some of the overturned folds are broken by small thrusts with small displacement. Evidence of thrusting beneath Borah Peak and in the Pass Lake area presented by Ross (1947, p. 1133) is discussed below.

EVIDENCE OF FAULTING

The following facts point to large scale Basin Range type fault in the area under discussion:

1. Displacement of the formations.
2. Physiographic evidence such as displacement of erosion surfaces, faceted spurs, and offsets in the ranges.
3. Distribution of the Challis volcanic series.
4. Disparity between broad valleys and intermittent streams when compared with the narrow gorges of the much larger Salmon River.

Displacement of the Formations.—The Brazer limestone caps most of the Lost River Range and White Knob Mountains. The same limestone formation underlies the Challis volcanic series in the downfaulted Thousand Springs Valley. Thus when the several altitudes occupied by the Brazer formation are compared, even with its pattern of folding and pre-Challis erosion taken into consideration, it appears that the series has been displaced 4,000-6,000 feet. The volcanic rocks have been stripped from the crest of the Lost River Range except in the north end near Meadow Peak but are preserved in the fault troughs and on the back slopes of the ranges. The relationship of displaced strata is well known just east of Willow Creek Summit where the Brazer limestone is faulted against Devonian strata (section B-B', fig. 1).

At the mouth of Lone Cedar Creek a small block of Lower Mississippian Milligen formation is faulted against the Silurian Laketown dolomite representing a stratigraphic throw of nearly 5,000 feet. This may be an intermediate block in a fault zone where the total displacement is even greater. Still another example of displacement of strata along the Lost River Fault occurs near Mackay, Idaho, where a large block of Brazer limestone nearly one-half mile in length crops out at the base of Mt. McCaleb. The rock is similar in composition and elevation to that of the Brazer limestone at the nearby Mackay Reservoir dam. The block is surrounded by alluvial fans and dips toward the base of the mountain 5,000 feet below the Brazer at the top of Mt. McCaleb. This is not a landslide block as shown by its size, uniform dip, and proximity to similar limestone at the Mackay Dam at the same elevation. Nor is it an exposure of Devonian dolomite from adjacent formations at the base of the mountain as shown by its limestone composition, its productid type brachiopods, and the peculiar thin wavy bands of chert typical of the chert in the Brazer limestone at the Mackay Reservoir and different from that in the Devonian dolomitic series. Besides these examples, the volcanic rocks are faulted against the older rocks, as along the Mackay Reservoir fault.

Physiographic Evidence.—There are at least two erosion surfaces developed in this part of southcentral Idaho (Ross 1937, p. 87-90). One with moderate relief underlies the Challis volcanics, the other has been developed upon a post-

Challis surface. Both have been notably displaced. The post-Challis erosional surface follows the initial stage of block faulting as shown by the preservation of Challis volcanic rock in the depressed areas and its erosion from the uplifted blocks. This erosion surface developed after tilting of the volcanics and was evidently developed during the Miocene and the Pliocene. Remnants of this erosion surface may be seen at Poverty Flat in the Bayhorse quadrangle and along the crests of the mountain ranges where the summits are in general accordant. Displacement of this surface is shown in sections A-A′ and B-B′, figure 1.

Most of the ranges are bordered on at least one side by relatively straight steep scarps with typical faceted spurs. This is true on both the southwest side of the Lemhi Range where Ross (1947) recognized a fault and along the southwest side of the Lost River Range where he did not. The Lemhi Range is composed dominantly of quartzite and is therefore more resistant to erosion. For this reason the facets are more in evidence in the Lemhi Range than in the Lost River Range where the formations are composed largely of massive dolomitic rocks near the base of the mountain and less resistant rocks higher up the mountain side.

Movement has been recent enough that broad rock pediments have not formed but instead thick alluvial deposits are piled at the base of the mountain overlying the downdropped blocks.

One of the distinctive phases of the physiography which can be explained most logically by faulting is the offset pattern of the ranges (fig. 1). There is a deep re-entrant into the Lost River Range east of Mackay and the counterpart of this in the Lemhi Range is located in the upper part of the Little Lost River. Neither of these offsets in the range can be attributed to erosion by the small streams emerging from them but are due to displacement along a fault. This is further indicated by the distribution of Challis volcanic series which occupies these re-entrants, and at Pass Creek, extends through the range to the Pahsimeroi Valley.

Distribution of Challis Volcanics.—The Challis volcanics were extruded upon the eroded surface underlain by Paleozoic rocks. The thickness no doubt varied because of contemporaneous faulting or topographic irregularities but there is

evidence that extrusives covered much of the total area. The fact that nearly every downwarped and downfaulted area contains the volcanics which also overlap the back sides of the tilled blocks argues for its much wider distribution, particularly as most of the faulting and nearly all of the relief is post-volcanics. Certain streams, such as Meadow Creek and perhaps Grouse Creek, now flowing on the Paleozoic strata, appear to have been let down from a cover of volcanics since removed by erosion. They rise on the southwest side of the crest and flow northward through the range. There are many straight or relatively straight contacts between the volcanics and the older rocks. Thus the distribution of of the volcanics is of great aid in delineating the positions of faults.

Disparity between Stream Flow and Valley Width.—It is notable that the Thousand Springs Valley, Antelope Flat, Little Lost River Valley and the Pahsimeroi Valley contain great thicknesses of Pleistocene and Recent alluvium. Most of the streams from the surrounding highlands have large alluvial fans. The present streams sink into the alluvium at the range borders and emerge as springs in the intermontane flats. Even the main streams in these flats are little more than intermittent streams at times during the year, as most sink into their alluvium; hence the name "Lost River." There is obviously a tendency to fill rather than to excavate the broad valleys. It may be argued that during the Pleistocene the streams were much large and that erosion took place then. It is likely true that the streams were larger, as is indicated by the huge fan deposits that are now being dissected by the small streams. Thus, filling was even more rapid during the times of greater precipitation, and erosion in the mountains was greater but not in the basins which were receiving rather than contributing sediments. The Thousand Springs Valley is an isolated pocket at the north end of the Big Lost River Valley and it is not being filled as rapidly as the part adjacent to the Lost River. Alluvium from the Lost River dams it, forming a marsh.

In contrast to the broad valleys with intermittent streams, the Salmon River, a much larger stream, cuts across the west and north end of the area under discussion. It rises in Central Idaho, flows through Stanley Basin, then cuts through

a very deep narrow gorge to Round Valley, which is a continuation of the graben between Lone Pine Peak and the Lost River Range. After crossing the broad valley, the river once more enters a narrow canyon and later re-emerges into other structural basins before plunging across the heart of Idaho where it is called "the River of No Return." Although there is some variation in rock hardness along the route, it is of minor consequence when compared with the structural control, as many of the formations transversed by the Salmon River are found in the other areas.

PRE-CHALLIS FAULTS

Leatherman Pass Fault.—The Leatherman Pass fault is one of the most easily recognized faults in the area under discussion. It parallels the west fork of the Pahsimeroi River and extends through Leatherman Pass (plate 1, fig. 1) where the Ordovician Kinnikinic quartzite is faulted against the Mississippian Brazer limestone, a stratigraphic throw of about 8,000 to 10,000 feet. This fault does not offset the crest of the range, neither does it noticeably offset the Challis volcanics in the vicinity of Mahogany Creek where it apexes with the Rock Creek-Mahogany Creek fault. Borah Peak is within a triangular fault block which is bordered by the two faults mentioned, and the prominent Lost River fault at the front of the range. This block in pre-Challis time was uplifted far higher than other parts of the range and, as mentioned, shows more intense deformation. This triangular block is referred to as the Borah Peak fault block.

Rock Creek-Mahogany Creek Fault.—A fault following Mahogany Creek and Rock Creek crosses the Lost River Range to the west of Borah Peak. The Borah Peak fault block is tilted westward so that the throw is not as great as on the Leatherman Pass side. This fault does not offset the crest of the range nor does it noticeably offset the Challis volcanics on the Pahsimeroi side of the range. Both the Leatherman Pass and Rock Creek-Mahogany Creek faults were mapped by Ross (1947). Tear faults within the Borah Peak fault block were also mapped by Ross.

Rattlesnake Springs Fault.—The stratigraphic section exposed in Grouse Creek in the northern part of the Borah

Peak quadrangle is broken by a fault which trends along the edge of the mountains past Rattlesnake Springs. This fault parallels the younger Basin Range faults. It is coupled with the Wino Basin fault in bounding the intervening fault block. When traced northward, however, it appears to extend beneath arched but unfaulted Challis volcanic rocks, and for that reason is classed with the pre-Challis faults. However, a prominent scarp overlooks the Challis volcanics at Rattlesnake Springs.

Wino Basin Fault.—The Wino Basin fault is also exposed in Grouse Creek and from there it parallels the westward-facing scarp as far as Meadow Peak. The age of this fault is difficult to tell but it appears to be covered by later Challis volcanics at the north end. In both the Rattlesnake Springs fault and the Wino Basin fault the volcanics are in place near the base of the scarps, suggesting either initial deposition against a scarp or more recent faulting. The volcanics were evidently thick enough to cover the crest of the mountains, for Meadow Creek cuts through the range isolating Meadow Peak and is evidently let down from a covering of volcanics. Yet because these faults do not appear to cut the volcanics they are discussed with the pre-Challis faults even though they parallel and have some similarity to the Basin Range type of faults. It is possible that movement occurred during extrusion of the volcanic series.

Upper Cedar Creek Fault.—The thrust faults are considered to be of pre-Challis age because of their origin during compressive stresses rather than during the stage of later normal faulting. There are few thrust faults noted in this part of Idaho. One of the most prominent is exposed in the canyon of Upper Cedar Creek a short distance northwest of Mt. McCaleb. The fault plane is essentially horizontal toward the front of the range (section C-C′, fig. 1), but it steepens to about 20 degrees to the northeast in the upper part of the canyon. The Brazer limestone has been displaced to the southwest, relative to the underlying folded dolomites, and the Milligen and Three Forks formations, being incompetent, have been pinched out in places, unlike the pattern mapped by Ross (1947) who shows the two formations relatively continuous. The thrust occurs at a bend in the

structural trend and dies out a mile or two in either direction along the range front. The talus between Mt. McCaleb and Upper Cedar Creek tends to obscure the thinning of the Milligen and Three Forks formations. Major Laramide displacements such as the Bannock overthrust (Mansfield, 1927) are usually to the east and northeast. If this is of Laramide age, it may therefore represent a small underthrust.

The Upper Cedar Creek fault was not mapped by Ross although his structural data corroborates its existence. The Brazer, Milligen, and Three Forks as mapped by him are in general parallel to the contour lines and thus nearly horizontal; whereas, dips in the older formations exposed in the canyon are steep toward the synclinal axis (fig. 1, C-C′) which exists in the position of his anticlinal axis. The whole base of the mountain from Lone Cedar Creek to the edge of the quadrangle near Upper Cedar Creek is mapped by Ross (1947) as Jefferson dolomite. This series rather consistently dips into the mountain 40 degrees. As there is no evidence of duplication and the structure is simple along the mountain face, a computed thickness of more than a mile may be obtained for the Jefferson dolomite, which is far greater than the 1,000 feet plus listed by Ross. The writer found Laketown dolomite exposed along the base of the mountain and even some darker dolomite similar to the Saturday Mountain formation exposed in places (plate 1, fig. 2). The stratigraphic section resembles that mapped by Ross north of Willow Creek Summit along Antelope Flat where the Jefferson crops out under similar conditions and overlies the Laketown dolomite with similar thickness.

Thrusting in the Pass Lake Region.—A thrust fault zone extending northward from Pass Lake beneath Borah Peak has been mapped by Ross (1947, p. 1134). This zone is broken by faults which Ross concluded were tear faults associated with thrusting. In this area of inferred thrusting a lens of dark-colored dolomite and associated clastic sediments is interbedded within the Kinnikinic quartzite. Deformation of such a thick massive quartzite formation favors yielding along the less competent zones and in the intercalated lens the dolomite is complexly deformed and the clastic beds are schistose. Ross (1947, p. 1134) states that "the Kinnikinic quartzite lies both above and below the thrust and the

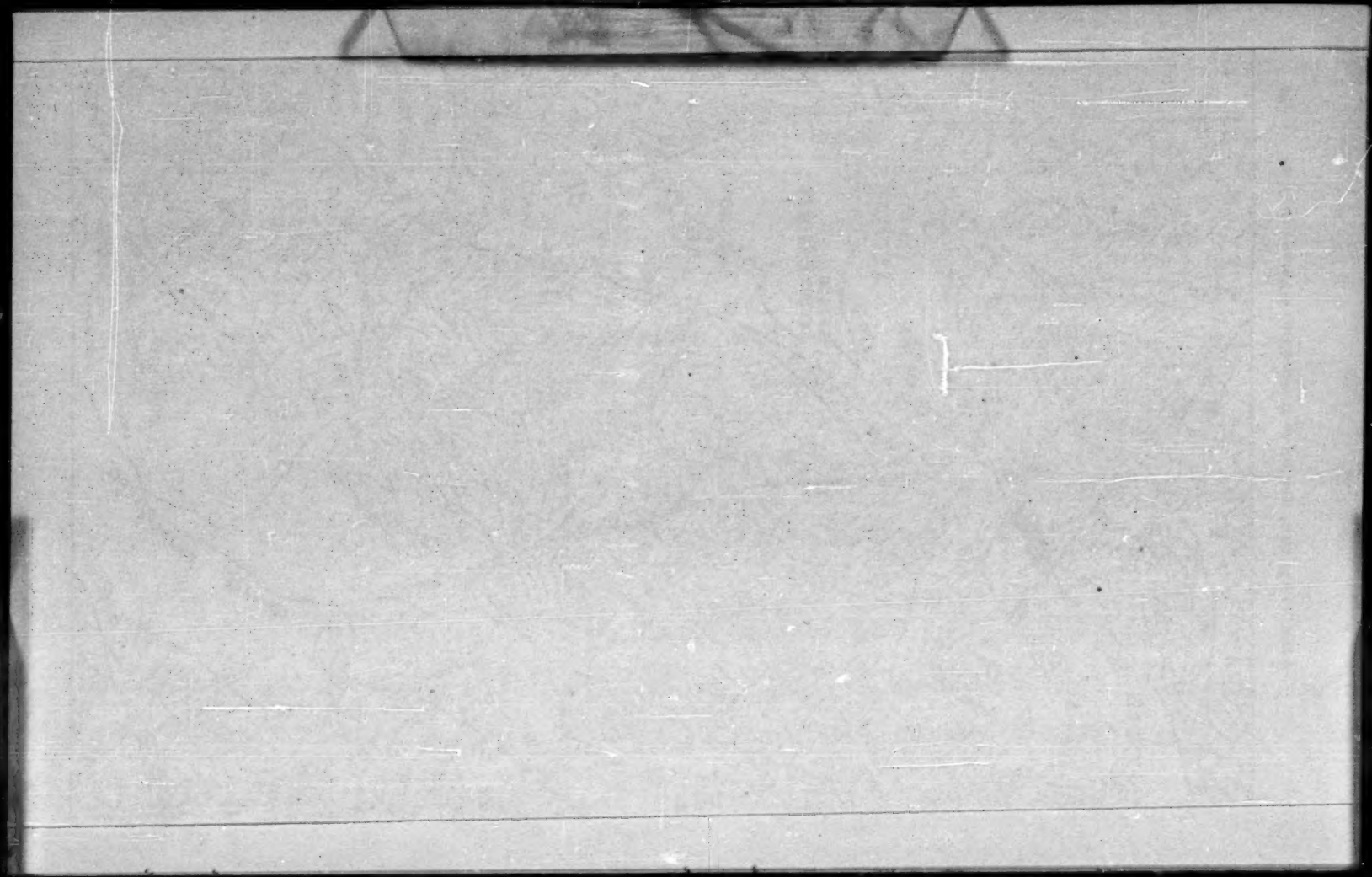

Fig. 1. Fault pattern in the northern part

part of the Lost River Range, Idaho.

zone of disturbance along the fault is occupied by intricately deformed beds that are, in part of Devonian age." Much of the "fault breccia" mapped by Ross is exposed at the top of the mountain in plate 1, figure 1, where it appears to be interbedded within the Kinnikinic formation rather than a segment of the Jefferson dolomite along a fault zone where its position between members of the Kinnikinic would be difficult to explain. Both the intercalated dolomite and the Jefferson dolomite are similar in appearance. Yet until adequate fossil evidence is presented, the Devonian age as well as the need for a thrust fault is questioned. Fossils from these beds examined by the writer were too poorly preserved to be diagnostic.

The Kinnikinic quartzite is badly fractured where it overlies the older quartzite and slate series at the head of Vance canyon (plate 1, fig. 1). The lower quartzite on either limb of the syncline seems to protrude into the overlying Kinnikinic quartzite, whether from initial relief or from thrusting was not surely determined. During the intense deformation there would undoubtedly be some movement and shattering along the contact of two unconformable massive quartzite series, but movement of more than a few feet drag during folding is not suggested. The fact that the basal Kinnikinic is purple, perhaps from the iron content of iron bearing clastic sediments derived from a weathered surface, and white above as the sea encroached farther upon the land, supports the conclusion that the Kinnikinic was deposited upon upturned slate and quartzite beds. It is only in this Borah Peak fault block that the basal Kinnikinic is exposed. Elsewhere in the region only the upper white beds are exposed and it may be for that reason that the purple quartzite was not considered by Ross to be Kinnikinic quartzite.

POST-CHALLIS FAULTS

Mackay Reservoir Fault.—A downfaulted block roughly triangular in shape includes Thousand Springs Valley and part of the Big Lost River Valley from the Mackay Reservoir to Copper Basin (fig. 1). A large area of Challis volcanics resting on the Brazer limestone, which is exposed in small buttes such as Chilly Buttes, occupies this depressed area. A relatively straight fault passes through the vicinity of the

Mackay Reservoir dam and trends southwestward to the east side of Copper Basin. The Challis volcanics are approximately 2,000 feet thick in the area between the dam and the basin. They rest on the Brazer limestone and are faulted against the same formation in the White Knob Mountains. The Brazer limestone of White Knob Mountains rises abruptly 1,000 feet above the volcanics; thus the indicated displacement is at least 3,000 feet. The fault, which may readily be seen on the Mackay topographic sheet by the difference in topography, is nearly straight and appears to be nearly vertical. This fault evidently extends at least to the south end of Copper Basin to a point near the Blaine and Custer county line. The tributary creeks of the Big Lost River rise in the Paleozoic highland, flow through deep glaciated valleys until they cross the fault and enter the broad basin carved in volcanics.

Thousand Springs Fault.—Another prominent scarp trends southward from the Lost River frontal scarp near Willow Creek Summit, borders the Thousand Springs Valley and extends southward toward the valley of the Big Lost River. This fault is distinct where it borders the Thousand Springs. Small remnants of volcanics lie next to the base of the scarp just south of the springs area. Displacement of the Brazer limestone is about 2,000 feet near the springs but it may be less where the fault enters the Lost River Valley to the south.

Lone Pine Fault.—The Lone Pine fault bounds the southwest side of the Antelope Flat-Round Valley graben which stretches from Willow Creek Summit to the Salmon River in the vicinity of Challis. This fault generally parallels the Lost River fault till it curves toward the mountain near Willow Creek Summit; a summit in the Paleozoic strata which, although depressed relative to the Lost River Range, still is not buried beneath alluvium as is the rock on either side. The throw on this fault at Lone Pine Peak is more than 3,000 feet; the straight, steep scarp is shown in plate 2, figure 1. A cross section of this graben (section A-A′, fig. 1) shows displacement both of the post-Challis erosion surface and of the volcanic series. It is highly improbable that a small stream could have excavated the broad depression from Antelope Flat northward, and the evidence of faulting along each margin indicates that this low area is on a graben block.

Ross (1937) fails to place a fault either along Lone Pine Peak or along the even higher scarp fronting the Lost River Range.

Lost River Fault.—A very prominent scarp borders the Lost River Range from Round Valley near Challis to the Snake River Plains near Arco, a distance of some 80 miles. The displacement is probably even more than the 5,000 feet that the peaks tower above the valley floor. Although the fault appears to be but a single break along much of the range front and high triangular facets are common, where it borders the Borah Peak fault block it is paralleled by several faults. Other parallel faults may lie beneath the valley alluvium.

With the exception of the badly deformed Borah Peak fault block, the formations nearly everywhere strike parallel to the range front and dip into the mountain. This sequence is again broken between Mt. McCaleb and Pass Creek near Mackay where the fault cuts across the axes of folds. At Pass Creek there is a prominent offset in the range and a split in the fault; one branch trends northward through the range where it borders the east side of a belt of Challis volcanics which has been downfaulted into the range, and the other branch continues northward along the front of the range. South of Pass Creek the strata again assume their characteristic strike paralleling the range front with the Brazer limestone at the top and the Silurian and Devonian dolomites at the base of the mountain. This offset in the range, and the tendency of the strata to strike parallel to the mountain front so uniformly, is caused by faulting and not by stream erosion of broad valleys.

Donkey Hills Fault.—A steep fault is exposed near the west end of Dry Creek Canyon where it cuts through the Donkey Hills. The fault extends northwestward, separating uplifted Paleozoic strata on the east from Challis volcanics and overlying Donkey fanglomerate on the west. The scarp of this fault is not particularly prominent, and it dies out to the north. This fault bears the same relationship to the Donkey Hills that the Lost River fault does to the Lost River Range, in that both of the blocks affected are offset on the southwest and tilted northeastward. However, geomorphic study points to much more active faulting in rela-

tively recent time in the Lost River Range. Lost River originally crossed the Lost River Range at Doublespring Pass and flowed into the Pahsimeroi Valley (Anderson, 1947). It was defeated by active uplift of the front of the range and diverted southeastward along the fault-formed valley. Later, glacial till filled the center of the former valley at Doublespring Pass. Dry Creek rises in the Lost River Range and flows across the Donkey Hills in a canyon nearly 2,000 feet deep (fig. 1). However, irrigation water from the now damaged Dry Creek Reservoir was piped around the south end of the Donkey Hills, and alluvium which spreads around the south end shows that glacial waters had this alternate route at one time. It is thus evident that Dry Creek maintained a course antecedent to post-Challis faulting across the hills as did the Big Lost River across the range throughout much of Late Cenozoic time. However, either faulting ceased earlier along the front of the Donkey Hills, or Late Cenozoic displacement was less; else the much smaller Dry Creek would easily have been defeated and diverted around the end of the hills as temporarily occurred during glacial times. The absence of a prominent scarp along the southwest side of the Donkey Hills indicates less Late Cenozoic displacement.

Lemhi Fault.—The prominent fault bordering the Lemhi Range is analogous to that of the Lost River fault. Ross mapped this feature in the Borah Peak quadrangle where the volcanics were faulted against the quartzite. One branch of the Lemhi fault trends northward along the head of the Little Lost River and the other continues northwestward. In between lies a depressed area of Challis volcanic rock in the re-entrant into the range. This belt of volcanics is similar to the belt that extends through Pass Creek Pass and northward between the Donkey Hills and the Lost River Range. Both Umpleby and Kirkham thought that this belt of volcanics occupied a former stream valley through the Lost River Range. If so, it was a pre-Challis river whose course was guided by initial faulting. However, it appears to be more structural than erosional. Anderson (1947) discussed the drainage history of this part of Idaho and proposed that streams flowing northward followed the Pass Creek-Wet Creek route through the Lost River Range and continued past the head of the Little Lost River through the Lemhi Range (this

pass evidently has no name). There seems to be little evidence to show that either of these passes was occupied by a stream in post-Challis time. The passes are due in part to faulting and in part to the headward erosion in the more easily eroded volcanic series. Even if a stream did flow northward, it was defeated long before the diversion of the Lost River from its route through Doublespring Pass. In the case of the latter stream, its valley is wholly erosional and is not dependent upon the location of a volcanic belt, unless originally superimposed from overlying volcanic rocks. The Lost River persisted in its course through the Lost River Range until a short time before late Wisconsin glaciation.

SUMMARY AND CONCLUSION

Origin of Faults.—The evidence favors at least two series of faults caused by independent forces. The older faults are largely compressional and include minor thrust, tear, and some normal faults. These may be in part pre-Laramide in age and further accentuated by Laramide deformation as proposed by Anderson (1948). The Paleozoic strata were folded prior to the intrusion of the batholith in Late Jurassic or Early Cretaceous time (Ross, 1936).

Faulting of the Basin Range type is predominantly post-Challis although initial movement may in some cases have accompanied or preceded extrusion. The age of the Challis volcanics, based on regional considerations and on paleontological data by Roland Brown, is given by Ross (1937, p. 68) as possibly of Oligocene age and hardly younger than early Miocene. Nolan (1943, p. 182), who reviewed faulting in the Basin and Range Province, indicated that displacements may have occurred in the early Oligocene and continued intermittently thereafter. Faults topographically manifested by scarps he concluded date back only to the late Pliocene or early Pleistocene. Normal faulting may have started just prior to or during extrusion of the volcanics but the largest movement has been later. Early faulting dropped the volcanic areas prior to development of the Pliocene erosion surface, and thus accounts for their preservation. Later faulting offset this erosion surface and was important in producing the topography of today which, as suggested by Nolan, is probably late Pliocene and Pleistocene. Movement

had generally ceased by late Pleistocene (upper Wisconsin) time as till and outwash of this age do not appear to be displaced.

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UNIVERSITY OF OREGON
EUGENE, OREGON

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ORIGIN OF "LAND HEMISPHERE" AND CONTINENTS

REGINALD A. DALY

ABSTRACT. The distribution of deep-sea basins and high-standing continents is a major problem of physical geology. Its solution, if ever found, must be by the method of trial and error. This paper describes one "trial" not hitherto brought to print. The rocky materials of our planet are generalized as "central core" overlain in succession by three silicate layers: thick "Sima," much thinner "Sialsima," and still thinner "Sial." All four constituents were developed in pre-geological time: Sima and probably Sialsima as world-circling shells; Sial, least dense, highest of all, continent-making, and largely concentrated in one hemisphere.

The vertical differentiation of the Sial and then the horizontal segregation are explained. Particularly with respect to the horizontal segregation the discussion is intensely speculative and the result is offered for criticism by experts in the physics and chemistry of the globe. Demonstration is now impossible, but the writer believes that even extreme speculation is warranted on this fundamental mystery, so little emphasized in scientific libraries.

INTRODUCTION

ACCORDING to averages the floor of the Pacific Ocean is lower than the surfaces of North America, South America, Europe, Asia, Africa, Australia, and the exceptional, ice-capped Antarctica by the respective amounts of about 5,000, 4,870, 4,620, 5,240, 5,030, 4,620, and 6,000 meters. In average the continental land surface stands above the mean depths of the Pacific, Atlantic, and Indian oceans by about 5,130, 4,470, and 4,800 meters respectively. Together the seven continents are largely concentrated in the "land hemisphere."

By use of the gravity-measuring pendulum and of the spirit-level-measuring deflections of the plumbline, it has been proved that each continent is not far from being in a state of almost perfect flotation on the earth's body. Its varied relief, conspicuous where a high mountain-chain looks down on plain or deep basin, demands notable strength for the visible rock. On the other hand, the quasi-flotation of the continent after much loss of material by secular denudation means great weakness in an earth-shell of depth. That such an "asthenosphere" exists (Daly, 1946) is further evident from the response of a continent to loading by a great ice-cap and to its unloading when the ice melted away. There is general agreement

that the weakness of the hidden shell is a dirct sign of increase of temperature far beyond the greatest depth reached by any bore-hole where thermal gradients have been measured. Further, as the geologist meditates about those experiments by both Nature and men, he cannot feel satisfied that the extra heat is all from the earth's radioactivity, for he must assume much primitive heat if he is to understand the shelled structure of our planet or the earth's asymmetry, the subject of the present inquiry.

The problem of the asymmetry is two-pronged. How and when were the light rock-materials segregated vertically? How and when were they segregated horizontally on a planetary scale? The attempt to give reasonable answers is to be described. First, high authorities dealing with the mutual relations among the recognized major constituents of the earth's body will be consulted. Then a plunge will be made into the dangerous sea of speculation about the quite different conditions of the earth's infancy.

During this somewhat prolonged exploration the writer has profited much by personal consultations with Dr. Harold Jeffreys, Dr. Fred L. Whipple, and Dr. Francis Birch, all of whom hoisted cautionary signals. No one of these friends should be held responsible for the actual results of using unsecured premises by one who confesses inability to test these by mathematical methods—the core of the matter.

PRESENT STRUCTURE OF THE EARTH

Discussion will be facilitated by making some generalizations with use of four names, three of which are of mnemonic character and in part familiar.

For reasons needing no recital on this occasion the writer prefers the view that the "core" of the earth with mean radius of about 3,500 kilometers is chiefly composed of metallic iron in alloyed form, essentially the material of the iron meteorites. Because seismic waves of the transverse kind are not transmitted through this mass, it is believed to be in a fluid, preferably liquid, state. There are indications that the core is composite and layered.

Diagnosis of the overlying earth-shell, about 2900 kilometers thick and extending to the tops of the highest mountains of the lands and to the floors of the oceans, is primarily a problem

for the seismologists aided by the findings of other specialists on the physics of the globe; a vital example of this help is a close determination of the earth's mean density.

The most thorough studies bearing on the nature of the thick earth-shell are those of Harold Jeffreys (1929) and Beno Gutenberg (1945). Both agree (1) that the material is silicatic, with density increasing downward (chiefly because of pressure), though even at bottom much smaller than that of the metallic core; (2) that from the mutual contact, a "discontinuity of the first degree," upward to a level averaging about 50 kilometers below the continental surface (the so-called Mohorovičić discontinuity) the material has properties apparently not very far from those expected in nearly homogeneous peridotite at the appropriate ranges of pressure and temperature; and (3) that as a whole the ultrabasic material has rigidity greater than that of steel under ordinary laboratory conditions, meaning by "rigidity" a degree of stiffness permitting the propagation of tranverse (shear) seismic waves at all levels and at the high velocities deduced from seismograms. As to cause of the rigidity Jeffreys emphasizes crystallinity for the material. Gutenberg (1939, 1945, 1948) accepts the idea for the top of the layer, but has found reason to assume a vitreous state for some of the material from the depth of some 80 kilometers to the depth of at least 180 kilometers. Of course both writers explain the rigidity as chiefly due to the high pressure. Seismological data suggest some chemical or phasal heterogeneity in the thick shell.

To the material of the ultrabasic sublayer as a whole the name "Sima" is here applied. It signifies abundance of silica and magnesium, a feature in common with the average stony meteorite.

Overlying the Simatic sublayer in the continental sectors of the globe are two others. The upper one averages 10 to 15 kilometers in thickness; the lower one about twice that. With some arbitrariness on the writer's part, the material of the former will here be called "Sial," a mnemonic recalling the fact, declared by direct vision and soundly based inference, that this sublayer is rich in quartz and alkaline feldspar.

Between Sial and Sima is the third sublayer, like the Sima invisible. Here wave-velocities average higher than those in the Sial and match well with the velocities expected if the

dominant material there is rich in silica and soda-lime feldspar. To this sublayer the barbaric name "Sialsima" is given in order to permit easy reference.

Seismologists have found growing evidence of the reality of the Mohorovičić discontinuity at the base of the Sialsimatic sublayer. They seem to agree that the two upper sublayers are composite both mineralogically and chemically; also that all three sublayers are mutually transitional, though not to the extent of masking the individuality of Sial and Sialsima.

The Sialic sublayer is not literally a "granitic layer," for by direct inspection geologists find the principal, granitoid rock (including orthogneiss) to be charged with countless dikes, sheets, and irregular injections of more basic nature, such as diabase, gabbro, norite, and peridotite, all risen from the depths. The Sialsima sublayer is composite for the same and other reasons. It can also be called the "intermediate layer," but the name "basaltic layer" is not justified by known facts, though it may include much basaltic material.

Similar study of the "crust" under the deep ocean, covering two-thirds of the globe, is handicapped by the invisibility of of the terranes and by the relative poverty of seismological data beyond the continental borders. Nevertheless, with the information already in hand, checked by the fact of a close isostatic relation between ocean and continents, some ideas about the proportions of Sial, Sialsima, and Sima concealed by the bottom sediments have won considerable probability.

West of the so-called "andesite line" in the western Pacific both Sial and Sialsima seem to be represented, but the Sial must be considered thinner than its equivalent at any continental interior and may be quite discontinuous. Possibly the same condition appears in the "Albatross Plateau" of the eastern Pacific off South America. Elsewhere and thus in the greater part of the Pacific basin there is no hint of Sial. According to Byerly (1930) the velocity of earthquake waves of the Love kind is such as to warrant belief that in this vast region there is a comparatively thin layer of rock with composition intermediate between Sial and Sima as if Sialsimatic in the sense intended by the present writer. This surface layer passes down into a much thicker one with the elastic properties of crystallized peridotite (frozen Sima).

The islands of mid-Atlantic and the existence of the largely

submerged "Mid-Atlantic Swell" or "Ridge" indicate the presence of Sial and doubtless Sialsima in that belt, 7,000 miles long and averaging something like 500 miles in width. To east and west of the "Ridge" the mean depth of water suggests a crustal composition much like that under the central Pacific.

The Indian Ocean lies on a "crust" of analogous variation. There the largely submerged "Murray Ridge" in the area of the Arabian Sea and its prolongation southward, and also the "Carlsberg Ridge" and "Seychelles Bank" seem to contain Sial and Sialsima. Elsewhere the Sial appears to be lacking, though the Sialsima may be represented.

This short account of the existing state of affairs is consonant with the general rule of almost perfect isostasy in all continental and principal marine areas of the globe, and gives a fair basis for speculative thought about the origin of "land hemisphere" and "water hemisphere."

PREVIOUS EXPLANATIONS OF THE ASYMMETRY

Some brief discussions of our problem have been published. For example, it has been suggested that the Pacific basin is a broad scar left after the moon was calved out of the earth. However, the main premise on which the idea is based is insecure for two reasons. First, there is in sight no agreed-upon cause for the partition; this is especially clear since Jeffreys (1935, p. 142) questioned the adequacy of G. H. Darwin's resonance theory for such fission. Secondly, no one has explained why the fission was delayed until the imagined crystallized Sial with present thickness and also the Sialsimatic layer were differentiated from the Simatic shell.

According to a quite different conception, the solid floor of the Pacific is the "outcrop" of a gigantic mass of once-liquid Simatic material brought up convectively as a unit, long ago and from the central region of the planet. In its downward path the same convective current is supposed to have carried on its back the originally world-circling Sial and jammed it into the hemisphere opposed to the ancient Pacific. The speculative result would be an approximate doubling of the thickness of the Sial by the inevitable crumpling, overthrusting, and underthrusting: hence a land hemisphere having structural complexity comparable with that of

the visible basement terranes of the continents. This speculation is affected, perhaps fatally, by its author's failure to describe an acceptable cause for the giant overturn and to provide a reason why the convection should have been on a hemispherical scale rather than occurring in much smaller "cells."

Inasmuch as no other, more satisfying theory of the earth's fundamental asymmetry seems to have been published, the present writer has yielded to the temptation of offering a new explanation for criticism. Its outline in the words of the following pages had been completed before a copy of W. S. Jardetzky's (1950) paper on "The problem of mountain ranges" was received in the mails. Therein was a reminder that, two years before, Jardetzky (1948) had developed still another hypothesis. This is based on the assumption that the young earth, when molten at the surface, was in zonal rotation: that, like the Sun and Jupiter, the earth had an angular velocity of rotation which was greatest at equator and decreasing regularly to each pole. A quotation from the 1948 paper summarizes Jardetzsky's idea concerning the essential cause of the "hemispherical" asymmetry. On pages 5 to 7 we read:

> "The first step in the solidification of a liquid globe would be the formation of a superficial layer, in which the velocities of floating bodies increased from the poles to the equator. The zonally distributed currents in this layer must long hinder the formation of a thin crust. But the cooling was continued and the free surface of the solids grew. Let us now consider the motion of a solid large enough to drift in several zones. Its velocity will have a certain mean value—the currents near the equator try to accelerate its motion, other currents will slow it down. It is at once obvious that a body having a large surface will capture, after some revolutions, all others floating in the same zones, for it will overtake the slowly moving ones or will be overtaken by the bodies floating with greater velocities . . . . We now assume that the greater drifting bodies would capture all the others and it seems probable that, when these first parts of the crust thickened enough they formed at last a single floating body. Thus we see that the hypothesis of zonal rotation of the Earth is favorable to the formation of a single continent, that is to say of a drifting body which will not cover the whole of the Earth's surface. During the next period the whole surface was solidified and there remained a single continental block."

Jardetzky then tries to show by special experiments how the single continent in the course of time would be torn asunder with the ultimate opening of the Atlantic and Indian

ocean basins, and this in such a way as to cause orogenic folding and thrusting in zones of the Andean and Hercynian types. These actions also are supposed to have been controlled by the zonal rotation of the planet.

The present writer finds it hard to believe that any zonal rotation postulated for an initially gaseous or gas-swathed earth could long persist after liquefaction took place. The enormous increase of viscosity would speedily damp out such differential rotation in latitude. Moreover, it is by no means certain that the earth at any stage was characterized by zonal rotation, so little understood as this property is in the case of either Sun or Jupiter. The new hypothesis, here presented, leads to some analogies with Jardetzky's scheme, but in principle follows a quite different chain of reasoning.

VERTICAL SEGREGATION OF THE SIAL

Among the oldest known rocks are quartzite and schists which can hardly be other than metamorphosed sandstones and argillites, clearly sedimentary products of the decay of older, extensive terranes of granite-like constitution. Those deposits were chiefly made in one or more large bodies of water. There is no reason to doubt isostatic equilibrium between such water-covered sector or sectors and the area or areas where the Sial kept its head above water.

Thought along these lines should be controlled by the best theory explaining the vertical segregation of the Sial. It is an open question as to whether its dominant constituent, now visible at the earth's rocky surface, is granite or granodiorite. Whichever it is, those writers who make "granitic layer" synonymous with what is here called the "Sialic layer" are so far justified in implying that the original differentiation represents in principle the answer to the famous old question: what is the origin of granite? Bearing on that subject there are two suggestions, one from outdoor Nature, and the other from laboratory experiments. The two kinds of evidence support each other and are compelling in a qualitative sense, but both need to be supplemented by bold theoretical reasoning before one can extrapolate to the conditions when a Sialic layer even only a few kilometers thick was developed.

The data from experiments in the laboratory have been most convincingly assembled by Dr. Norman L. Bowen in his

masterly book entitled "The Evolution of the Igneous Rocks" (1928), as well as in many papers (1915, 1919, 1922) reporting on the physical chemistry of molten silicates studied by himself or by others with his guidance. One result of these taxing researches is proof of the profound effect of fractional crystallization on the chemical composition of the liquids successively residual during the slow cooling of those melts. So fortified with facts from his crucibles, Bowen drew vital conclusions regarding some wholesale changes during the very much slower cooling of natural melts, magmas: (1) that at a late stage in its crystallization a basaltic melt has an interstitial liquid of granitic composition; (2) that the heavy, early-formed crystals, demonstrably basic or ultrabasic, tend to sink as individuals or as local assemblages, making the residual liquid more and more acid, ultimately of granitic composition, and because of lower density rising toward the top of the crucible; (3) that such gravitative, "two-phase" differentiation should in Nature be expedited in large bodies of basic melts if "squeezed" during their slow crystallization. Further, he came to the important idea (1928, p. 320) that basaltic melt or magma is itself an analogous differentiate from a peridotitic (not dunitic) earth-shell, formerly molten. Worthy of special remark is the second chapter of his book where he gives weighty reasons for rejecting the old doctrine that the differing compositions of igneous rocks are to be explained by the immiscibility of their respective melts.

In 1893 the present writer became immersed in the granite problem and is still immersed. During many seasons of field-work in regions where diabasic, gabbroid, and noritic sills are numerous, particularly areas in North America, east and west, and in South Africa, he found many of these bodies to exhibit no granitic phases at the roofs though some sills were as much as 100 to 1,000 feet in thickness. In a number of instances roof phases of quartz-rich rock, closely resembling typical granite, were discovered, but because of a kind of chemical consanguinity with invaded quartzite and metargillite (probably water-charged sandstone and argillite at the time of igneous invasion), he could not determine what proportion of this roof material is a genuine differentiate of juvenile, uncontaminated gabbro (basalt) now underlying. Prolonged labor in field and laboratory has therefore not afforded full

satisfaction with the theory that the Sial is a straightforward fractional derivative of more basic, more ferromagnesian, material. With the recent development of the hypothesis presented in this paper a way to greater faith in the efficiency of fractional crystallization has been opened.

The vertical, gravitational segregation is best understood on the assumption that the first and immediately succeeding crusts of our planet underwent many successive founderings of the kind described by Sir William Thomson (Lord Kelvin) on page 483, volume 1, of his "Treatise on Natural Philosophy" (1883). He founded this idea of what may be called "major stoping" on Bischof's pioneer experiments demonstrating the notable contraction of igneous matter in freezing. Since 1883 many other measurements have been made, showing the common types of igneous rocks to decrease in density by 8 to 12 per cent when heated to a completely molten state at atmospheric pressure. The percentages decrease only slightly as the pressure on the rock increases to some thousands of atmospheres. In consequence: a block of crystalline periodotite would have to sink in molten peridotite; a block of crystalline basalt or diorite would sink in molten basalt; a block of granite, granodiorite, quartz diorite, or diorite would sink in molten granite or granodiorite. Hence it seems right to think that a stable surface layer of granite or granodiorite, the leading constituent of the Sial, could have been the result of the fractionation of a molten peridotitic earth-shell only after many downstopings, remeltings, and gravitative risings of the successive melts more silicious than peridotite. If that occurred on a planetary scale, the conditions must have been vastly different from those now ruling.

Among those conditions is one to deserve particular attention in the sequel but here mentioned because it involved a special additional threat to the stability of the many crusts—a threat that was temporary in the sense that it had to be much abated in the first few millions of years of earth history. The anticipated point is this: At that early time the moon was close to the earth and made great body-tides in it. The day was only a few hours long, so that every two or three hours any new crust was subjected to strong, ever-varying, positive and negative tensions. It is natural to conclude that such young crust was thereby cracked into separate floe-like pieces, each

of which was liable to upending and foundering. The more silicious, lower-melting part of each sunken mass would be remelted first in the hot underlying liquid and rise *en masse* to make contact with the atmosphere. There renewed crusting, foundering, and differential melting in depth would result in gravitative separation of intrinsically still more silicious, light material from the intrinsically heavier. After many such cycles, step-by-step, a stable granitic or granodioritic layer, so light as to be unsinkable even after solidification, would be formed at the surface.

Thus the writer has reached the speculative view that the making of the world's granitic material was essentially completed just after the earth became an independent traveler in space. Further, as set forth elsewhere (Daly, 1933), the visible batholiths and other large bodies of "granitic" rock, along with rhyolitic outflows, all dating from early Precambrian to the Pleistocene, are products of many remeltings of the primitive Sial and Sialsima where deeply depressed by orogenic forces. In other words, he attributes the origin of the main constituent of the Sial chiefly to the fractional crystallization of a more basic earth-shell, much of this differentation occurring long before any visible body of it was emplaced.

Petrologists in general seem to have no rooted objection to the thought that Sial and Sialsima were differentiated by fractional crystallization from peridotite which was molten at the earth's surface. According to the seismologists material almost identical with peridotite chemically is now represented in the 2,750-kilometer silicate shell resting on the "iron core" with radius of nearly 3,500 kilometers. What have cosmologists to say about these ideas?

A good many of those authorities regard meteorites as fragments of a disrupted small planet and furnishing a clue to the chemistry of the earth's interior. From that and other clues Jeffreys (1929) developed his well-known hypothesis, according to which the infant earth had two main constituents —a nickel-iron core with chemical composition like that of the average iron meteorite, and a shell of peridotite chemically like many stony meteorites. While fully conscious of the difficulty of establishing any extant theory of origin for the solar system (see his 1939 paper), he still sees no good reason

for rejecting his idea of 1929, that the earth was initially gaseous and therefore with viscosity so low as to permit early gravitative assembling of "droplets" of nickel-iron in total amount great enough to make the existing core. Thoroughly insulated against the cold of outer space, the core has remained liquid to this day, as evidenced by the observations of seismologists. Jeffreys explained the silicate shell as essentially the stuff of the stony meteorites and at an early stage made highly homogeneous by convection and stirring within the shell itself.

F. L. Whipple (1948), W. M. Latimer (1950), and others have suggested that the earth and other planets may have been derived from a "cold cloud" or "dark nebula." This parent is assumed to have been a mixture of "dust" and gases with hydrogen and helium dominant, the cloud having a mean density so low as to approximate that of the gas in a vacuum tube. Each planet is taken to be a condensate of a small fraction of the cloud. According to Whipple the condensation was begun by the pressure of light from the stars and then greatly speeded by the collapse of the planetary fraction because of its self-gravitation. By the collapse the temperature had to increase. Whipple thinks it possible that the increase was sufficient to give a molten earth; Latimer finds the resulting temperature nowhere greater than a few hundred degrees Centigrade. None of this group of authors discusses adequately the amount of additional rise of temperature because of "heats of formation" which may have been developed when silicates, oxides, and sulphides were formed during the collapse. When account is taken of both sources of heat it seems possible that the cold-cloud hypothesis also permits one to postulate: (1) temporary liquidity at the surface of the earth; and (2) prolonged convection in the silicate shell, giving this a nearly homogeneous, peridotitic composition.

It is hard to understand how the surface of the rocky material could have reached so high a temperature unless a thick, heavy atmosphere protected the melt from the cold of outer space. It is logical to suppose both atmosphere and liquid to have originally and temporarily contained considerable amounts of hydrogen and helium, the staple constituents of Sun, star, or nebula. The molecular velocities of those and other permanent gases would soon drive the primitive at-

mosphere away, to be lost in outer space. With more delay those in the peridotite-gas solution beneath would escape, but, while they did remain in the liquid, they aided in its differentiation and also in the re-solution of crystals sunk down from the surface or from levels close to it. The first lot of crystals to sink would be ultrabasic themselves and their solution in depth would not make much change in the composition of the absorbing peridotite. Then, too, if the liquid shell was in more or less lively convection, its comparative homogeneity in depth would be preserved.

According to the adopted theory of fractional differentiation the whole process, controlled by escape of both gas and heat in the top layer of the silicate shell, had to be the assembling of granitoid material at the surface. Even after the solidification of this acid differentiate it would remain in stable flotation on the denser liquid beneath and thus become the chief constituent of the Sial throughout geological time.

HORIZONTAL (HEMISPHERICAL) SEGREGATION OF THE SIAL; PANGÆA

We now pass to our second principal query: what was the mechanism compelling the Sialic material to pile most of itself into one hemisphere, "Pangæa," leaving nearly two-thirds of the opposite hemisphere "basined" and ready to receive all or nearly all of the ocean? For ease in following this remainder of the general argument the answer may be stated at once: The great horizontal segregation is attributed to the gravity pull of the moon on the moon-made tidal bulges or protuberances of the molten earth at an early time when moon and earth were close together.

The book "Astronomy" by H. N. Russell, R. S. Dugan, and J. Q. Stewart (pages 294-299) contains needed data concerning the present range of the terrestrial tide due to the moon alone. The range of the water tide in the open ocean far from continental land is now about 2.5 feet. The range of the lunar body-tide in the earth is now about 1.2 feet. If the earth were molten and thus quite inelastic, the range of the same tide would be about 4 feet (estimate given verbally by H. Jeffreys).

George H. Darwin (1898, p. 278; 1908, pp. 103, 455) proved beyond cavil that earth and moon were separated initial-

ly by no more than a small fraction of their present center-to-center distance, which has the round figure of 240,000 miles; and that after the lapse of a million years or so the distance was still relatively small. He further showed the range of the lunar tide to have varied inversely as the cube of the separating distance, while the tidal retardation of the earth's rotation varied inversely as the sixth power of the distance. In the following table, column 1 gives sample distances; column 2, the corresponding fractions of the distance at present; column 3, the corresponding multiples for the range of the existing body-tide; column 4, the computed ranges in feet; and column 5, the corresponding multiples of the retarding force now exerted by the moon on the earth's rotation. All values of the table are only approximate.

TABLE 1

1	2	3	4	5
Distance in miles	Fractions of present distance	Multiples	Ranges in feet	Corresponding multiples of retarding force at present
12,000	1/20	8,000	32,000	64,000,000
20,000	1/12	1,728	6,912	22,985,984
24,000	1/10	1,000	4,000	1,000,000
30,000	1/8	512	2,048	262,144
34,285	1/7	343	1,372	117,649
40,000	1/6	216	864	46,756
60,000	1/4	64	256	4,096
80,000	1/3	27	108	729

It needs no emphasis that in comparison the retarding effect of the solar tide when earth and moon were close together was quite negligible.

That there had to be a powerful brake on the spinning of the young earth was made clear by Darwin (1898 and 1908). He saw that because of the viscosity of the silicate material the upbuilding of the tidal bulge on the body of the young earth had a notable time-lag, and that the necessary effect was to throw the bulge forward in the direction of the earth's rotation. By mathematical methods he described the inevitable consequences: (1) the slowing of the rotation by the moon's gravitative pull on the protuberance; and (2) the driving of the moon to greater and greater distance along a spiral of revolution around the earth. He found it impossible to

compute accurately the minimum, initial, distance separating moon from earth, but he did find it to have been but a small part of the present distance. This discovery led him to speculate about the origin of the moon, asking himself first: Did the infant earth rotate so fast that large fragments of it were thrown off in the equatorial belt, to be later by their mutual gravitation gathered into a ball, the moon, safely launched as a satellite in permanent revolution around the parent?

On the well-based assumption of constancy of total angular momentum in the system he had no hesitation in answering the question in the negative. Yet he had a feeling that some principal facts relating to the existing system could be most readily explained if the calving hypothesis be retained. Hence came his famous theory of a molten earth, drastically affected by the solar tides. He supposed these, by resonance, to grow to heights so great that the planet's gravitational attraction on their substance became insufficient to hold the ever-mounting liquid; great fragments of it, endowed with rapid tangential motion, flew off to distances so great that they were unable to fall back and so became the lunar ball. As Darwin himself well knew, this beautifully designed hypothesis faced inherent difficulties, later shown by Jeffreys (1930) to be probably fatal.

Nevertheless Darwin's discussion suggests that if in some unknown manner a large part of the moon's material was torn out of the earth, the initial center-to-center distance between planet and satellite may have been no more than about 12,000 miles, the moon's orbit being circular. If, on the other hand, the moon was captured, her orbit would have had to be strongly elliptical and the perigee distance may have been as small as 12,000 miles. In either case the lunar body-tide in the earth must have had relatively great amplitudes. Using the data of the preceding table, a crucial effect of the moon's gravitational pull on the material of each of the two opposing protuberances will be considered.

First we recall Darwin's proof that each protuberance or bulge had to be carried forward in the direction of the earth's rotation. It may be noted that he assumed a relatively high viscosity for the young planet. On page 126 of his "Scientific Papers," volume 2 (1908) he gave actual figures.

If the present writer is not wrong in his arithmetic, the assumed viscosity is that of hard pitch at 0° C. (about 10^{12} poises). In fact, Darwin remarked that the assumed viscosity was that of a substance which would "be called a solid in ordinary parlance." He was able to extend his integration to the stage when the month was somewhat more than five hours long, the center-to-center distance between moon and earth being no more than about 10,000 miles. At that time the maximum attraction of the moon on unit mass of the tidal protuberance nearer the moon was about 1/180 of the earth's attraction on the same unit mass. The moon's attractive force was therefore about 5 dynes per gram of matter near the top of that protuberance. At the top of the antipodal protuberance the lunar pull was only about one dyne per gram. Thus with respect to the earth's rotation the moon's retarding force exerted on the nearer protuberance was about five times the accelerating force exerted at the antipodes, As Darwin concluded, the net effect of the couple was to retard the earth's rotation and to drive the moon away along a spiralling course. Thus the day has come to be 24 hours long and the synodical month somewhat more than 29 days long.

Of more immediate interest is the fact that the horizontally directed force is also a shearing force operating at all levels in the liquid planet but with greatest intensity at the surface. Any horizontal displacement due to the shear would be easiest close to the surface, one reason being the very rapid increase of viscosity in the liquid as the pressure upon it grew with increase of depth.

Horizontal displacement of importance could not occur until cooling and loss of gas began to develop masses of solid matter at the surface. That stage would probably be reached within a period of some centuries. Then and during subsequent centuries the vertical, magmatic, differentiation of the liquid proceeded. Let us review the drama once again. It is impossible to picture in detail the many downstopings of crustal blocks, the uprisings of residual liquids due to the remelting of the partly crystallized pieces of crust which sank, and the upsurges of juvenile gases released from the primary peridotitic melt. But, according to sound petrogenic theory, the ultimate result would be the assembling of granitoid material at the surface. Even after crystallization such material had

attained density so low that it was unsinkable in liquid peridotite or the liquids matching the denser types of gabbro, dolerite, or diabase, though liable to engulfment in liquid of andesitic or, possibly, of basaltic composition. Two-phase convection of the kind continued at intervals of geological time, but probably to a depth not much greater than that of the Mohorovičić discontinuity, where by slow cooling of the planet the peridotite began to crystallize. Because of the accompanying increase of density similar two-phase overturnings of the peridotite itself might be expected to happen at still longer intervals. Without stopping to consider the bearing of this last deduction on the theory of post-Cambrian orogenesis, thought will now be centered on the fate of the granitoid material at the surface.

The rapid changes in the field of force were simultaneous with rapid change in the distribution of mass. Hence it is natural to suppose that the crystallized granitoid material would not constitute a world-circling crust but rather a number of free-floating, macula-like floes. At the base of each the horizontally-directed shearing force derived from the lunar pull was concentrated, because the floe is solid and endowed with some strength. In consequence the floe as a unit was displaced in the direction opposite to that of the earth's rotation. Let it be imagined that one floe, enlarged in the north-south direction and thus to latitudes where the displacing force grew smaller and smaller, was overtaken by floes not so extended and not so much retarded by the moon's attraction. By a process of crumpling agglutination, aided by continued cooling, the especially elongated macula, now appropriately called the master floe, became thicker and increasingly able to resist the west to east drag of the more swiftly moving liquid beneath.

It is easy to see that the master floe would become charged with an internal, horizontally directed, compressive stress. This stress would increase with the march of time and also in the direction of the drag by the substratum. In principle this is a deduction made by Darwin (1908, p. 189) when he wrote of the "wrinkling" of the tidally disturbed earth shortly after it became partnered by the moon. His "wrinkles" had north-south axes at the equator but with increasing distance to north and south they had to assume a northeastward trend in the northern hemisphere and a southeastward trend in the

southern hemsiphere. He described the action as a "screwing" deformation and added the remark (1898, p. 307): "If the material yielded very easily I imagine that the wrinkles would be small, but if it were so stiff as to yield with difficulty they might be large."

But there may have been other types of deformation. The master floe had some brittleness, however small, and hence liability to low-angled faulting with underthrusts and overthrusts. The resulting thickening of the floe would further increase the horizontally directed shear of the floe over the strengthless, still liquid Sima and also hasten the agglutinating process.

According to our postulates the gravitative differentiation of the original peridotitic liquid was facilitated by successive downstopings (founderings) and by the influence of much gas that had been dissolved when the liquid was laden with a heavy atmosphere. When this atmosphere, by flight into outer space, was reduced to a relatively trivial mass, both superficial and deeper-lying liquid still retained a temporary excess of gas, which aided mere cooling in the magmatic differentiation. The sunken material was re-dissolved in depth (where de-gassing was less pronounced), but being largely ultrabasic itself kept the top of the peridotite shell comparatively close to the Sialic layer.

Further, let it be conceived that the master floe had by agglutination come to include all of the Sialic material separable under the conditions described; also that the tidal couple of forces affecting the planet was still so powerful as to expose the stripped, more basic liquid to direct radiation of its heat to outer space. At its own surface this liquid would quickly lose heat and much of its small residuum of gas and become covered with a permanent Sialsimatic (perhaps basaltic or gabbroid) crust.

Meantime the moon's pull still keeps power to crumple and thicken the master floe. Let it be supposed that therewith the master floe, when fully developed with its relatively low density, average thickness approaching 10 kilometers, and a structure of much complexity, covers only about one-half of the globe. Its surface stands high above that of the stripped hemisphere, which is basined and ready to receive the water of the ocean; the ancient Pacific is overlooked by the dry land of Pangæa.

This speculative conclusion is not in conflict with the good, geological evidence that that primitive Pacific basin has been somewhat narrowed, since the beginning of the Devonian period, by displacements of large blocks of the Sial.

Another relevant remark is in order. The described crumpling and thrusting of the Sial demanded the expenditure of energy. However, the total expenditure would hardly be as much as one per cent of that robbed from the earth's rotation when the day was lengthened from five hours to twenty-four hours. The young earth had plenty of energy to supply the internal heat developed by tidal friction and to drive the moon to its present distance of 240,000 miles.

RESIDUAL QUERIES

The argument of this essay is assuredly tenuous. It is based on a chain of assumptions inevitably plagued with uncertainty and on a hardihood in speculation all the more apparent when additional troubles are given due weight.

(1) According to a leading premise the Sialic material of the earth began to be differentiated at the surface after the lapse of a few tens of thousands of years at most. Still more time would be required for the horizontal segregation. Here, then, is a grave question: was the horizontal segregation possible during the period when the moon was still near enough to the earth to do the work? A final answer must be left to those more competent to find it.

(2) To them another difficulty may well be referred. Hitherto there has been no mention of the fact that Antartica, straddling the South Pole, and the lands at high latitudes in the Northern Hemisphere have roughly the same thickness of Sial as that in the equatorial belt. Is it possible that during or after the horizontal segregation of the Sial the earth's skin as a whole was displaced with reference to the axis of rotation so as to bring the edge of the Sialic accumulation beyond each Pole? Was the Sial crumpled and thickened at the Poles during the inevitable reduction of the earth's ellipticity?

(3) Again, can the proposed genetic scheme, implying a former, initial, uninterrupted Sial of the "land hemisphere" be reconciled with the existence of the Atlantic and Indian ocean basins? In answer, is there any better explanation of

these basins, proved to be at least in large part much younger than the Pacific basin, than that the former are broad gashes in the once-continuous Pangæa? In spite of difficulties in the physics of the process and in spite of rather dogmatically expressed scepticism on the part of some (by no means all) geologists and geophysicists, the writer (Daly, 1923, p. 448) cannot rid himself of the idea that Wegener (1924), while wrong in his geophysical argument, was right in proposing his well-known theory of continental migration with its corollary, the post-Devonian origin of the two ocean basins of the Old World. The present writer (Daly, 1926, p. 275) has suggested that the migration may have been in the form of gigantic landslides, the sliding-slopes having been slowly generated by the slower cooling of the "land hemisphere," covered by a long-intact Sial which was specially heated by radioactivity for nearly three thousand million years. Hitherto radioactivity has been ignored because it could have had no practical importance during the rapid changes supposed to accompany the formation of Pangæa.

(4) The reader will note too that no reference has been made to the effect of tidal friction between ocean and terrestrial crust. A leading reason for this omission is doubt that any important body of liquid water existed before the Sial was "hemispherically" segregated. Is this doubt to be shared by those cosmologists who credit a once-molten peridotitic layer at the earth's surface? Has the writer sinned in stressing friction set up by body tides in the infant planet?

(5) Can the "wrinkling," crumpling, and thrusting of the rocks first built into Pangæa be identifiable in even the oldest visible terrane of Archean age? The terrane is, to be sure, structurally complex, but the visible complexity may well be the result of distortions connected with massive intrusions into the young crust and with the distortions during post-Archean orogenic revolutions. Hence any attempt to support the explanation offered for Pangæa by direct field evidence of this kind seems destined for failure.

(6) And a final test: can the moving picture of the pre-geological earth gear well with the moving picture of geological time as inferred from field observations? Among the major events thus recorded are: the occasional great outpourings of molten basalt with its chemical and time relations to the

world's eruptive sequences: the epochal growth of mountain chains; the physical and chemical changes of the asthenosphere from the early Archean to the present day; and the secular shifts of sealevel with respect to continental lands. To prove all these changes to have been logical results of the pre-geological conditions described in the foregoing pages would be a superhuman task. But there remains the human urge to continue speculation. So impelled, the writer has published a book based on such adventure. There he (Daly, 1933) emphasized the fact that to understand the evolution of the face of our planet and its underpinning one must be primarily concerned with the supply of heat from the earth's interior. The temperature and thickness of the crust were thought to have been changed by two different processes: convectional overturns of deep-lying earth-shells, occurring at long intervals of time; and by radioactivity, especially potent in continental sectors capped with the Sial. In those sectors basalt, an early and principal differentiate of a still more basic, much thicker earth-shell, was temporarily liquefied and thus made eruptible, endowed with assimilative power, and weakened to the point of permitting the development of mountain chains. However, as shown in the present paper, the writer believes in the advisability of more seriously allowing for the role of juvenile gas in the grand evolution.

According to the new view of the young earth its silicate material was in gaseous solution with hydrogen and helium and covered by a thick, heavy atmosphere of the same stellar gases. Both gases and (presumably also water vapor) are imagined to have had excessive quantities in the shell of liquid peridotite even after the flight of much of the permanent gas. At ever-decreasing rate these volatiles were diffused upward and outward, in free phase or molecule by molecule. At the surface of the liquid shell the loss of fluxing gas was particularly rapid and hence crystallization is thought to have been faster than if due to radiative cooling alone. Convection was therefore speeded. The sunken solid material was re-dissolved in deeper layers still being enriched with gas risen from the depths and therefore relatively superheated. Thus layer by layer the silicate shell was convectively stirred, the crust was alternately thickened and thinned, and the basalt of the Sial-sima alternately frozen and melted. That the escape of the

originally absorbed, juvenile gases is still going on is suggested by recent analyses of volcanic emanations, in which measured quantities of both hydrogen and helium are reported. The final result of this short review of the possible role of juvenile gas in helping to organize the earth as an engine working through geological time is, however, not to express belief but to put this question also before geochemist and geophysicist.

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Division of Geology
Harvard University
Cambridge, Massachusetts

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THE CONCENTRATION OF CERTAIN CHEMICAL ELEMENTS IN THE SOILS OF ALASKAN ARCHAEOLOGICAL SITES

H. J. LUTZ

ABSTRACT. The content of phosphorus, nitrogen, potassium and calcium was determined in the soils of two Alaskan native village sites and in adjacent soils bearing natural forest growth. The food used by primitive man in Alaska was largely of animal origin and was relatively high in the chemical elements mentioned. During the course of time the soil of the village sites was greatly enriched with the result that there has been a 50 to 175-fold increase in phosphorus, a 3 to 7-fold increase in nitrogen, a 4 to 6-fold increase in potassium and a 2 to 12-fold increase in calcium.

IT is a common occurrence for foresters, and others whose work takes them into the field, to encounter ancient native village sites along the Alaskan coasts and rivers. As a rule a village site may be identified by its highly advantageous situation, by the depressions or other evidences of house locations, and, perhaps best of all, by the nature of the vegetation. Hrdlička (1937) and other anthropologists, (Anonymous, 1941), who have worked in Alaska have commented on the fact that the vegetation of old village sites usually differs in floristic composition and in *color* from the adjacent undisturbed vegetation. It is significant that the vegetation of the village sites is not only unusually luxuriant, but is also much darker green, presumably an effect of a relatively high level of soil fertility. Among the plants encountered on old village sites on Kodiak Island the most common is reported to be the stinging nettle, a species which is generally regarded as nitrophilous, that is, a "nitrate plant." As indicated by the vegetation, and as suggested by Hrdlička, chemical conditions in the soil of the village sites appear to have been altered by human agencies. The purpose of this note is to report the concentration of certain chemical elements in the soil of two such sites.

So far as is known to the writer, Arrhenius (1931, 1934) was the first to point out, from his extensive studies in Sweden, that the content of phosphorus was unusually high in the soil of old village sites, some of them dating back to the Stone Age. The food used by primitive man, whether of animal or

plant origin, was relatively high in phosphorus and all the organic refuse remained in, or closely adjacent to, the village. The Alaskan sites are actually village sites and kitchen middens combined. During the course of time the soil was enriched in various chemical elements but most especially in phosphorus, which in the soil tends to be "fixed" in forms that render it resistant to losses by leaching. In 1939 Castagnol reported accumulations of phosphorus in the soils of ancient village sites in Indochina which were analogous to those reported by Arrhenius in Sweden. Notably high concentrations of phosphorus in old village sites were later noted in Thailand by Pendleton (1943). Thorp (1942) remarked that farmers in the United States have noted that the soils of old Indian villages are more productive than adjacent soils. He speaks of "...man-induced fertility migration in soils." Thomas (1947) commented on the unusually high concentration of bases in the soil of old house sites in Uganda.

During the summer of 1949 three composite sets of samples of soil were obtained from an old village site near the mouth of the Russian River, where it empties into the Kenai River, on the Kenai Peninsula, Alaska. This village site is on a relatively flat bench. The area supports a very heavy growth of grasses and other herbaceous plants, unusually dark green in color. Numerous pits or depressions mark the former location of dwellings, presumably of the semi-subterranean type. The upper 6 inches of soil was sampled at each location by four or more borings within a radius of approximately 50 feet and the samples were composited in the field. Three such sets of samples were collected from as many different locations within the area of the village site. Samples of soil from undisturbed white spruce [*Picea glauca* (Moench.) Voss.] forest stands, obtained for another purpose, were available for comparison. In 1950 comparable samples were obtained in Southeastern Alaska from the Auke village site about 10 miles northwest of Juneau and from an adjacent second-growth stand of Sitka spruce [*Picea sitchensis* (Bong.) Carr.].

Analyses were performed following standard methods, as described by Peech, *et al.* (1947). The exchangeable calcium and potassium was extracted with a normal neutral solution of ammonium acetate. Readily soluble phosphorus was extracted with a 0.002 normal solution of sulfuric acid, buffered

with ammonium sulfate to pH 3.0. Nitrogen was determined by the Kjeldahl method. The results follow in table 1; all constituents are expressed in terms of the elements, not the oxides. Values for phosphorous are in parts per million; these values may be converted to percentages by multiplying by 0.0001.

TABLE 1

Chemical Analyses of Soils from Two Alaskan Village Sites and from Comparable Forest Stands.

	Phosphorus, ppm	Nitrogen, per cent	Potassium, per cent	Calcium per cent
	Russian River village site			
Location 1	2048	1.021	0.036	0.261
Location 2	1360	0.742	0.044	0.654
Location 3	1590	1.178	0.048	0.708
Average	1666	0.980	0.043	0.541
	White spruce forest			
Location 1	4	0.162	0.012	0.035
Location 2	39	0.118	0.009	0.051
Location 3	60	0.109	0.009	0.051
Average	34	0.130	0.010	0.046
	Auke village site			
Location 1	1250	1.005	0.022	0.717
Location 2	282	1.263	0.028	1.068
Location 3	1079	0.799	0.026	0.697
Average	870	1.022	0.025	0.827
	Second-growth Sitka spruce forest			
Location 1	6	0.217	0.003	0.262
Location 2	5	0.318	0.005	0.294
Location 3	5	0.475	0.004	0.432
Average	5	0.337	0.004	0.329

It is obvious that human occupancy of the Russian River village site has resulted in a tremendous increase in the content of phosphorus in the soil—an increase amounting to nearly 50-fold. Increases in the other elements, although of lesser magnitude, are also notable. In the village-site soil nitrogen shows a 7-fold increase, potassium a 4-fold increase and calcium a 12-fold increase.

In the soil of the Auke village site there has been an increase in the phosphorus content of about 175-fold. Nitrogen shows an increase of about 3-fold, potassium 6-fold, and the calcium content has been doubled.

With such profound increases in the soil fertility of the village sites it is not surprising that the vegetation of these areas should differ from that normal for the region in species composition, luxuriance, and color.

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ALASKA FOREST RESEARCH CENTER
JUNEAU, ALASKA
AND
SCHOOL OF FORESTRY
YALE UNIVERSITY
NEW HAVEN, CONNECTICUT

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DISCUSSION

THE SO-CALLED "TEMPLE OF JUPITER SERAPIS"

A recent letter from George E. McCracken, Professor of Classics in Drake University, includes the following comment:

"For the benefit of future authors of text-books on geology, I beg leave to call attention to a minor error which now appears in several of the more widely used texts in this field.

"As an example of the phenomenon of diastrophism there is usually cited, quite correctly, a building still to be seen at Pozzuoli, the small city and port which gives its name to the gulf forming the western arm of the Bay of Naples. The structure which exhibits the borings of *Lithodomus lithophagus* in its columns at a height of eleven to nineteen feet above the surface of the ground, and consequently offers proof of diastrophism in that area, is called variously 'the temple of Jupiter Serapis' or 'the temple of Serapis.' What source there is for mentioning Jupiter in this connection, I have been unable to discover, but one would not normally expect to find the Roman god Jupiter worshipped conjointly with the Egyptian god Serapis. On the other hand, the designation of the structure as a temple of Serapis is the result of a local error, a type of confusion found in many localities in Italy.

"What is quite certain, however, is that the building is no temple at all. The anonymous German archaeologist who wrote the description in Baedeker's guide to *Southern Italy and Sicily* (Leipzig, 1930, pp. 115-6) says that it was either a market (*macellum*) or, perhaps, a bathing establishment. The latter possibility is ignored by the equally anonymous Italian scholar who contributed the corresponding passage to L. V. Bertarelli's *Guida d'Itália del Touring Club Italiano: Itália Meridionale, Secondo Volume, Nápoli e Dintorni* (Milan, 1927, p. 334). As the openings in the thirty-six small chambers are said to be alternately on the exterior and the interior, the identification of the building, which was restored after the earthquake of 63 A.D., and therefore must be earlier than that date, as a market, rather than as a bath, seems much more plausible."

After an exchange of letters Professor McCracken wrote, for additional information, to Dr. Albert W. Van Buren, who continues to live in Italy after many years spent as Professor of Archeology at the American Academy in Rome. Van Buren replied that the literature on the old ruin at Pozzuoli is enormous; he selected six references as the most significant, and recommended particularly a short article by Nevio Degrassi (1946), which scholars accept as conclusive in its identification of the ruin on epigraphic evidence. This article is in Italian, and Professor G. Lincoln Hendrickson, Professor Emeritus of Latin and Greek Literature at Yale, kindly translated it for me. The main subject of the paper is an inscription on a marble slab that was found in the ruined structure at Pozzuoli. When it was first studied this inscription was obscured with grime, and critical words such as *macellum* could not be deciphered. A recent study of the cleaned stone reveals the inscription to be the original dedication of the structure as a "macellum,

with ornaments and meritoria." The latter word, Degrassi explains, was the technical designation of small rooms or cells rented to merchants using the market. Thus, as Degrassi points out, the inscription confirms the conclusion of earlier scholars, since Beloch in 1890, that the so-called *Serapeum* was in reality not a temple, but a market place. The fullest exposition of this view was made by the French scholar Ch. Dubois in 1907.

Charles Lyell first visited the old ruin in 1828, and in the twelve editions of his famous *Principles of Geology* three of the marble columns of the supposed temple, bearing marks made by marine organisms, were figured and described as eloquent testimony to depression and later elevation of the land. The twelfth edition, published in 1875, devotes many pages to description and discussion of the old "temple," with the following summary of arguments on which the accepted identification was based. (1) Among a number of images found in excavating the ruins was one of the Egyptian god Serapis. (2) An excavated marble column carries an inscription, "in very obscure Latin," setting forth a contract with builders to keep in repair certain public edifices, of which one was the Temple of Serapis, described as being near or toward the sea. (3) Pozzuoli (formerly Puteoli) was the port through which passed most of the Roman trade with Alexandria, the chief seat of the worship of Serapis. (4) Lyell was informed by the scholar Sir Edmund Head that at Alexandria there was a Serapeum "of the same form as this temple at Puzzuoli,[1] and surrounded in like manner by chambers, in which the devotees were accustomed to pass the night, in the hope of receiving during sleep a revelation from the god, as to the nature and cure of their diseases." (Lyell, 1875, vol. 2, p. 169).

Lyell was convinced by the sum of available evidence that the old edifice was a house of worship erected to the Egyptian god, and he spoke of it unequivocally as the Temple of Jupiter Serapis. Strangely his detailed and lucid discussion does not mention the apparently incongruous linking of mighty Jupiter with a foreign god that for a time was specifically under ban by the Roman Senate as an object of worship. Textbooks of geology have consistently followed Lyell's identification of the old structure, though some speak of it simply as the Temple of Serapis. Clearly, however, this designation is made untenable by archeologic research since 1890. Conclusions from this later study appear to be fully accepted in modern European literature dealing with the ruin. As McCracken notes, guidebooks speak of the structure as a market.

[1] Lyell's consistent spelling of the name differed from the spelling accepted at present.

The current edition of *Enciclopedia Italiana* carries a large halftone view of the familiar columns and the surrounding space, with the legend "Il macellum, detto tempio di Serapide" (The public market, known as Temple of Serapis).

Professor McCracken is to be commended for pointing out this long-entrenched error. Geologists are of course interested primarily in the evidence furnished by the columns on crustal movement. However, all parts of the record should be as accurate as possible.

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CHESTER R. LONGWELL

YALE UNIVERSITY
NEW HAVEN, CONNECTICUT

REVIEWS

Fundamentals of Acoustics; by LAURENCE E. KINSLER and AUSTIN R. FREY. Pp. vii, 516; numerous figs. New York and London, 1950 (John Wiley & Sons, Inc., and Chapman & Hall, Ltd., $6.00).—This is a book that may well become a standard text in its field. Although developed from the author's notes in a course given to graduate students in Engineering Electronics, it is well suited to advanced undergraduate or graduate courses in either physics or communication engineering. It presupposes a knowledge of the fundamentals of mechanics and electricity and some facility with calculus (including partial derivatives). The authors have been careful to avoid the use of mathematical analysis beyond the level of the undergraduate. They have likewise used restraint in the use of the standard roadblocks to students such as "It can easily be shown that....". The authors have an interesting lucid style.

The fundamental theory of acoustics is developed in the first nine chapters, which include an excellent analysis of the properties of vibrating strings, bars, membranes and plates as well as the propagation of sound waves through fluid media. This material could form the basis of a one-semester course in the fundamentals of acoustics.

The remaining seven chapters treat applications including loud speakers, microphones, architectural acoustics, underwater acoustics, ultrasonics, etc., and are written so as to be self-sufficient chapters to allow omission of any in a two-semester course.

The usefulness of the book as a text is increased by the inclusion of a large number of illustrative problems. The acoustical terminology is conventional following the proposals of the American Standards Association. The pleasure in using the text is increased by an excellent format.

HENRY A. FAIRBANK

Classical Mechanics; by H. C. CORBEN and PHILIP STEHLE. Pp. xvii, 388; numerous figs. New York and London, 1950 (John Wiley & Sons, Inc., and Chapman & Hall, Ltd., $6.50).—*Classical Mechanics* is a fairly inclusive work, devoted to the transition from an elementary to an advanced classical mechanics formalism, as this formalism is presently used in modern physics.

The standard subject matter of mechanics is treated in five compact chapters on Hamiltonian and Transformation Theory, as well as a chapter on rigid bodies which introduces quaternions. Where it is relevant, parallel use is made of both tensor and standard vector notation.

Other chapters emphasize modern developments in mechanics. For example, there is a well-written chapter on linear vector spaces, followed by the theory of small oscillations of conservative systems, and its application to the vibrations of molecules. This latter section is detailed and complete. There is a unique chapter which is devoted to a brief exposition of the properties of quasi-co-ordinates and quasi-momenta, non-central forces, and an instructive section on the analogy between transformation theory and thermodynamics. To round out this survey of modernized Classical Mechanics, a well-handled chapter on Relativity Theory is included.

The motion of a charged particle in an electromagnetic field is treated in several places. This culminates in a short final chapter concerning the betatron, synchrotron, and synchro-cyclotron. Where it becomes relevant, there is reference to the Bohr Theory as a limiting case.

By way of criticism, it might be stated that the notation is occasionally somewhat inconsistent. In addition, the uninitiated might feel that the section on differential geometry, in which tensor notation is introduced, was overcondensed; that is, more examples and elaboration would have made the whole work more self-contained.

In conclusion, *Classical Mechanics* is a good reference work and an advanced text, with a broad, compact coverage. N. STONE

The Biochemistry of the Nucleic Acids; by J. N. DAVIDSON. Pp. ix, 163; numerous figs., 4 plates. Methuen's Monographs on Biochemical Subjects. New York and London, 1950 (John Wiley & Sons, Inc., and Methuen & Co., Ltd., $1.75).—This book by J. N. Davidson presents a concise but thorough source of information on the present state of knowledge on nucleic acid biochemistry. The book is one of the excellent series of *Methuen's Monographs on Biochemical Subjects.* The author summarizes much information on the physical and chemical structure and properties of polynucleotides, nucleoproteins and components of nucleic acids. Recent chromatographic methods along with ultra-violet absorption, histochemical and chemical procedures for estimations of nucleic acids are well discussed. Much of the book is devoted to a review of the biological aspects of nucleic acids. It is in this special field of nucleic acid research that Dr. Davidson is actively engaged and can write with authority. The data on the content of nucleic acids in tissues, cell cytoplasm and nuclei are presented in convenient tables. Several chapters deal with the evidence for activity of the nucleic acids in such biological processes as mitoitic division, protein synthesis, embryonic induction and transformation of bacterial types. Studies of the biosynthesis of the nucleic acids are also reported.

Although by no means extensive, this book can be highly recommended to students and research investigators in biology and biochemistry as a readable and reliable source of reference and of general orientation on this important subject.

E. J. KRUGELIS

Sequoia National Park; by FRANÇOIS E. MATTHES; edited by FRITIOF FRYXELL. Pp. x, 136; 124 figs. Berkeley, California, 1950 (University of California Press, $3.75).—In 1938, the late François E. Matthes, a student of the Sierra Nevada for more than 30 years, prepared three brief folios on the geology of Sequoia National Park, California, for the use of the park's ranger naturalists. Fritiof Fryxell has combined these three folios into a single volume. Fryxell has made only minor changes in editing the work, and the photographs and text are essentially those of the original folios.

The book is an attractive and instructive photographic album on the geomorphology of the Sequoia region, from the western Sierra foothills to the great fault scarp on the east. The 120 excellent photographs comprise most of the book. They are grouped in eleven chapters which are devoted to particular land forms or geomorphic processes common in the park. Matthes' text consists of short discussions introductory to the chapters and of detailed explanations of all photographs.

One outstanding chapter describes and effectively illustrates the four uplifted Cenozoic erosion surfaces which Matthes identified and named in this part of the Sierra Nevada. From the surfaces Matthes interprets the westward tilt of the Sierra block as the result of four distinct movements. The first occurred in the early Cenozoic and the last in the early Pleistocene. The chapters on exfoliation domes and avalanche erosion and the discussions of the influence of jointing on topography are especially valuable. Matthes believes that avalanches are very important agents of erosion in the High Sierra.

The book is provided with a glossary and is well adapted to the use of the interested nongeologist. The many splendid photographs and Matthes' significant interpretations will interest also many geologists, especially geomorphologists.

WILLIAM H. HAYS

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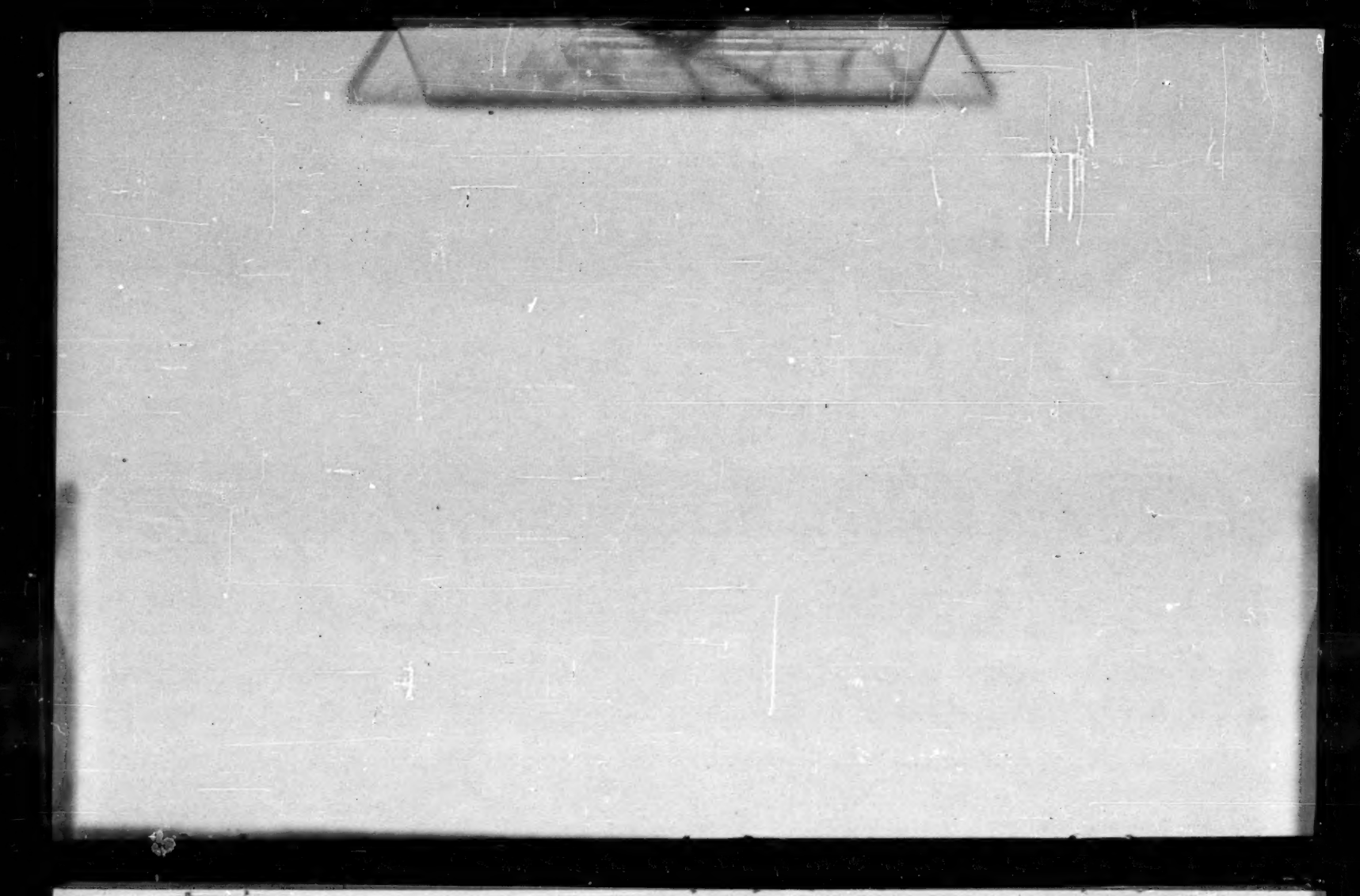

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